

**METHOD, SYSTEM AND PROGRAM PRODUCT SUPPORTING  
USER TRACING IN A SIMULATOR**

**Cross Reference to Related Application**

[0001] The present application is related to U.S. Patent Application Serial No. \_\_\_\_/\_\_\_\_, \_\_\_\_ (Docket No. AUS92000223US1), which is assigned to the assignee of the present invention and is incorporated herein by reference in its entirety.

**Background of the Invention**

**1. Technical Field:**

[0002] The present invention relates in general to designing and simulating digital devices, modules and systems in a distributed simulation environment, and in particular, to the declaration, compilation and use of trace arrays within a simulation model to store trace data of interest.

**2. Description of the Related Art:**

[0003] Verifying the logical correctness of a digital design and debugging the design, if necessary, are very important steps in most digital design processes. Logic networks are tested either by actually building networks or by simulating networks on a computer. As logic networks become highly complex, it becomes necessary to simulate a design before the design is actually built. This is especially true when the design is implemented as an integrated circuit, since the fabrication of integrated circuits requires considerable time and correction of mistakes is quite costly. The goal of digital design simulation is the verification of the logical correctness of the design.

[0004] In a typical automated design process that is supported by a conventional electronic computer-aided design (ECAD) system, a designer enters a high-level description utilizing a hardware description language (HDL), such as VHDL, producing a representation of the

various circuit blocks and their interconnections. The ECAD system compiles the design description into a format that is best suited for simulation. A simulator is then utilized to verify the logical correctness of the design prior to developing a circuit layout.

[0005] A simulator is typically a software tool that operates on a digital representation, or simulation model of a circuit, and a list of input stimuli representing inputs of the digital system. A simulator generates a numerical representation of the response of the circuit, which may then either be viewed on a display as a list of values or further interpreted, often by a separate software program, and presented on a display in graphical form. The simulator may be run either on a general-purpose computer or on another piece of electronic apparatus, typically attached to a general-purpose computer, specially designed for simulation. Simulators that run entirely in software on a general-purpose computer will hereinafter be referred to as "software simulators". Simulators that are run with the assistance of specially designed electronic apparatus will hereinafter be referred to as "hardware simulators".

[0006] Usually, software simulators perform a very large number of calculations and operate slowly from the user's point of view. In order to optimize performance, the format of the simulation model is designed for very efficient use by the simulator. Hardware simulators, by nature, require that the simulation model comprising the circuit description be communicated in a specially designed format. In either case, a translation from an HDL description to a simulation format, hereinafter referred to as a simulation executable model, is required.

[0007] It is frequently desirable for a simulation user to be able to analyze the results of a simulation run following completion of the simulation run. Accordingly, trace files containing events of interest detected during a simulation run are often constructed to permit a simulation user to review and analyze the simulation run. Such trace files may be built, for example, through the execution of a custom high-level language (e.g., C or C++) program that extracts signal values from the simulation model during simulation and stores the signal values within custom designed data structures.

[0008] The present invention recognizes that conventional techniques for constructing trace files tend to be labor intensive in that simulation users may be forced to construct custom programs and data structures to extract from the simulation model and store simulation data of interest. Moreover, conventional software techniques for building trace files tend to be computationally intensive during simulation, meaning that such conventional techniques degrade simulation performance, particularly for hardware simulators.

[0009] Accordingly, the present invention recognizes that it would be useful and desirable to provide improved methods, systems and program products for specifying and generating trace arrays and simulation trace files.

## SUMMARY OF THE INVENTION

[0010] In one embodiment of the present invention, one or more entities within a simulation model are specified with one or more statements in one or more hardware description language (HDL) source code files. In addition, a trace array for storing trace data generated through simulation of the simulation model is specified in one or more statements in the one or more HDL files. The HDL files may subsequently be processed to create a simulation model containing at least one design entity and a trace array within the design entity for storing trace data regarding specified signals of interest.

[0011] All objects, features, and advantages of the present invention will become apparent in the following detailed written description.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself however, as well as a preferred mode of use, further objects and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

[0013] **FIG. 1** is a pictorial representation of a data processing system;

[0014] **FIG. 2** depicts a representative hardware environment of the data processing system illustrated in **FIG. 1**;

[0015] **FIG. 3A** is a simplified block diagram illustrating a digital design entity that may be instrumented in accordance with the teachings of the present invention;

[0016] **FIG. 3B** is a diagrammatic representation depicting a simulation model that may be instrumented in accordance with the teachings of the present invention;

[0017] **FIG. 3C** is a flow diagram illustrating of a model build process that may be implemented in accordance with the teachings of the present invention;

[0018] **FIG. 3D** is a block diagram depicting data structures that may be instrumented in accordance with the teachings of the present invention;

[0019] **FIG. 4A** is a simplified block diagram representative of an instrumentation entity;

[0020] **FIG. 4B** is a simplified block diagram of a simulation model instrumented in accordance with the teachings of the present invention;

[0021] **FIG. 4C** illustrates exemplary sections of HDL syntax that maybe utilized in accordance with the teachings of the present invention;

[0022] **FIG. 4D** is a flow diagram depicting a model build process in accordance with the teachings of the present invention;

[0023] **FIG. 4E** is a block diagram representation of memory data structures constructed in accordance with the teachings of the present invention;

[0024] **FIG. 5A** is a logic diagram representation of a runtime disable mechanism in accordance with the teachings of the present invention;

[0025] **FIG. 5B** is a block diagram representation of functional units utilized to execute the method and system of the present invention on a hardware simulator in accordance with the teachings of the present invention;

[0026] **FIG. 6A** is a simplified gate level representation of an exemplary counting instrument with a runtime disable feature and automatic clocking adjustment in accordance with the teachings of the present invention;

[0027] **FIG. 6B** is a simplified timing diagram illustrating automatic clocking adjustment of counting instrumentation;

[0028] **FIG. 7** depicts an alternative counting means that may be employed for counting events detected by instrumentation entities in accordance with the teachings of the present invention;

[0029] **FIG. 8A** illustrates a conventional finite state machine that may be instrumented with an embedded checker in accordance with the teachings of the present invention;

[0030] **FIG. 8B** depicts a conventional finite state machine design entity;

[0031] **FIG.8C** illustrates a hardware description language file including embedded instrumentation in accordance with the teachings of the present invention;

[0032] **FIG. 9** depicts a hardware description language design entity included embedded instrumentation in accordance with the teachings of the present invention;

[0033] **FIG. 10A** is a block diagram illustrating a simulation model containing a number of design and instrumentation entities;

[0034] **FIG. 10B** depicts a data structure for declaring an event within a simulation model in accordance with one embodiment of the present invention;

[0035] **FIG. 10C** illustrates a list of extended event data structures for the simulation model in **FIG. 10A**;

[0036] **FIG. 10D** depicts a data structure for declaring an event within a simulation model in accordance with an alternate embodiment of the present invention;

[0037] **FIG. 11A** is a block diagram illustrating a simulation model in which the hierarchical event processing of the present invention is applicable;

[0038] **FIG. 11B** depicts a set of input port mapping comments for performing hierarchical processing of simulation model events in accordance with a first embodiment of the present invention;

[0039] **FIG. 11C** illustrates a set of input port mapping comments for performing hierarchical processing of simulation model events in accordance with a second embodiment of the present invention;

[0040] **FIG. 12A** depicts a representative target design entity with an instrumentation entity containing random instrumentation logic implemented in accordance with the teachings of the present invention;

[0041] **FIG. 12B** illustrates an exemplary HDL file for implementing instrumentation logic within an HDL design entity in accordance with the teachings of the present invention;

[0042] **FIG. 13** depicts an exemplary simulation model in which trace arrays are implemented in accordance with the present invention;

[0043] **FIG. 14** is a more detailed block diagram of a trace array in accordance with the present invention;

[0044] **FIG. 15** is a high level logical flowchart of an exemplary process by which an RTX directs execution of a testcase against a simulation model and storage of trace data from trace arrays within the simulation model to trace files;

[0045] **FIG. 16** illustrates an exemplary trace file in accordance with one embodiment of the present invention; and

[0046] **FIG. 17** depicts a trace analysis tool including a set of trace reader API routines for accessing and reading a trace file following a simulation run.

## DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0047] With reference now to the figures, and in particular with reference to **FIG. 1**, there is depicted a pictorial representation of a data processing system 10 with which the present invention may be advantageously utilized. As illustrated, data processing system 10 comprises a workstation 12 to which one or more nodes 13 are connected. Workstation 12 preferably comprises a high performance multiprocessor computer, such as the RISC System/6000 or AS/400 computer systems available from International Business Machines Corporation (IBM). Workstation 12 preferably includes nonvolatile and volatile internal storage for storing software applications comprising an ECAD system, which can be utilized to develop and verify a digital circuit design in accordance with the method and system of the present invention. As depicted, nodes 13 comprise a display device 14, a keyboard 16, and a mouse 20. The ECAD software applications executed within workstation 12 preferably display a graphic user interface (GUI) within display screen 22 of display device 14 with which a digital circuit designer can interact using a keyboard 16 and mouse 20. Thus, by entering appropriate inputs utilizing keyboard 16 and mouse 20, the digital circuit designer is able to develop and verify a digital circuit design according to the method described further hereinbelow.

[0048] **FIG. 2** depicts a representative hardware environment of data processing system 10. Data processing system 10 is configured to include all functional components of a computer and its associated hardware. Data processing system 10 includes a Central Processing Unit ("CPU") 24, such as a conventional microprocessor, and a number of other units interconnected via system bus 26. CPU 24 includes a portion of data processing system 10 that controls the operation of the entire computer system, including executing the arithmetical and logical functions contained in a particular computer program. Although not depicted in **FIG. 2**, CPUs such as CPU 24 typically include a control unit that organizes data and program storage in a computer memory and transfers the data and other information between the various parts of the computer system. Such CPUs also generally include an arithmetic unit that executes the arithmetical and logical operations, such as addition,

comparison, multiplications and so forth. Such components and units of data processing system 10 can be implemented in a system unit such as workstation 12 of FIG. 1.

[0049] Data processing system 10 further includes random-access memory (RAM) 28, read-only memory (ROM) 30, display adapter 32 for connecting system bus 26 to display device 14, and I/O adapter 34 for connecting peripheral devices (e.g., disk and tape drives 33) to system bus 26. RAM 28 is a type of memory designed such that the location of data stored in it is independent of the content. Also, any location in RAM 28 can be accessed directly without having to work through from the beginning. ROM 30 is a type of memory that retains information permanently and in which the stored information cannot be altered by a program or normal operation of a computer.

[0050] Display device 14 provides the visual output of data processing system 10. Display device 14 can be a cathode-ray tube (CRT) based video display well known in the art of computer hardware. However, with a portable or notebook-based computer, display device 14 can be replaced with a liquid crystal display (LCD) based or gas plasma-based flat-panel display. Data processing system 10 further includes user interface adapter 36 for connecting keyboard 16, mouse 20, speaker 38, microphone 40, and/or other user interface devices, such as a touch-screen device (not shown), to system bus 26. Speaker 38 is one type of audio device that may be utilized in association with the method and system provided herein to assist diagnosticians or computer users in analyzing data processing system 10 for system failures, errors, and discrepancies. Communications adapter 42 connects data processing system 10 to a computer network. Although data processing system 10 is shown to contain only a single CPU and a single system bus, it should be understood that the present invention applies equally to computer systems that have multiple CPUs and to computer systems that have multiple buses that each perform different functions in different ways.

[0051] Data processing system 10 also includes an interface that resides within a machine-readable media to direct the operation of data processing system 10. Any suitable machine-readable media may retain the interface, such as RAM 28, ROM 30, a magnetic disk,

magnetic tape, or optical disk (the last three being located in disk and tape drives 33). Any suitable operating system and associated interface (e.g., Microsoft Windows) may direct CPU 24. For example, the AIX operating system and AIX Windows windowing system can direct CPU 24. The AIX operating system is IBM's implementation of the UNIX™ operating system. Other technologies also can be utilized in conjunction with CPU 24, such as touch-screen technology or human voice control.

[0052] Those skilled in the art will appreciate that the hardware depicted in FIG. 2 may vary for specific design and simulation applications. For example, other peripheral devices such as optical disk media, audio adapters, or chip programming devices, such as PAL or EPROM programming devices well-known in the art of computer hardware and the like, may be utilized in addition to or in place of the hardware already depicted. In addition, main memory 44 is connected to system bus 26, and includes a control program 46. Control program 46 resides within main memory 44, and contains instructions that, when executed on CPU 24, carries out the operations depicted in FIG. 4D and FIG. 4E described herein.

[0053] Simulated digital circuit design models are comprised of at least one and usually many sub-units referred to hereinafter as design entities. FIG. 3A is a block diagram representation of an exemplary design entity 300 in which the method and system of the present invention may be implemented. Design entity 300 is defined by a number of components: an entity name, entity ports, and a representation of the function performed by design entity 300. Each entity within a given model has a unique name (not explicitly shown in FIG. 3A) that is declared in the HDL description of each entity. Furthermore, each entity typically contains a number of signal interconnections, known as ports, to signals outside the entity. These outside signals may be primary input/outputs (I/Os) of an overall design or signals connecting to other entities within an overall design.

[0054] Typically, ports are categorized as belonging to one of three distinct types: input ports, output ports, and bi-directional ports. Design entity 300 is depicted as having a number of input ports 303 that convey signals into design entity 300. Input ports 303 are

connected to input signals 301. In addition, design entity 300 includes a number of output ports 306 that convey signals out of design entity 300. Output ports 306 are connected to a set of output signals 304. Bi-directional ports 305 are utilized to convey signals into and out of design entity 300. Bi-directional ports 305 are in turn connected to a set of bi-directional signals 309. An entity, such as design entity 300, need not contain ports of all three types, and in the degenerate case, contains no ports at all. To accomplish the connection of entity ports to external signals, a mapping technique, known as a “port map”, is utilized. A port map (not explicitly depicted in FIG. 3A) consists of a specified correspondence between entity port names and external signals to which the entity is connected. When building a simulation model, ECAD software is utilized to connect external signals to appropriate ports of the entity according to a port map specification.

[0055] Finally, design entity 300 contains a body section 308 that describes one or more functions performed by design entity 300. In the case of a digital design, body section 308 contains an interconnection of logic gates, storage elements, etc., in addition to instantiations of other entities. By instantiating an entity within another entity, a hierarchical description of an overall design is achieved. For example, a microprocessor may contain multiple instances of an identical functional unit. As such, the microprocessor itself will often be modeled as a single entity. Within the microprocessor entity, multiple instantiations of any duplicated functional entities will be present.

[0056] Referring now to FIG. 3B, there is illustrated a diagrammatic representation of an exemplary simulation model 329 that may be utilized in a preferred embodiment of the present invention. Simulation model 329 consists of multiple hierarchical entities. For visual simplicity and clarity, the ports and signals interconnecting the entities within simulation model 329 have not been explicitly shown. In any model, one and only one entity is the so-called “top-level entity”. A top-level entity 320, is that entity which encompasses all other entities within simulation model 329. That is to say, top-level entity 320 instantiates, either directly or indirectly, all descendant entities within a design. Simulation model 329 consists of top-level entity 320 which directly instantiates two instances, 321a and

**321b**, of an FXU entity **321** and a single instance of an FPU entity **322**. Each instantiation has an associated description, which contains an entity name and a unique instantiation name. For top-level entity **320**, description **310** is labeled “TOP:TOP”. Description **310** includes an entity name **312**, labeled as the “TOP” preceding the colon, and also includes an instantiation name **314**, labeled as the “TOP” following the colon.

[0057] It is possible for a particular entity to be instantiated multiple times as is depicted with instantiations **321a** and **321b** of FXU entity **321**. Instantiations **321a** and **321b** are distinct instantiations of FXU entity **321** with instantiation names FXU**0** and FXU**1** respectively. Top-level entity **320** is at the highest level within the hierarchy of simulation model **329**. An entity that instantiates a descendant entity will be referred to hereinafter as an “ancestor” of the descendant entity. Top-level entity **320** is therefore the ancestor that directly instantiates FXU entity instantiations **321a** and **321b**. At any given level of a simulation model hierarchy, the instantiation names of all instantiations must be unique.

[0058] In addition to FXU entity instantiations **321a** and **321b**, top-level entity **320** directly instantiates a single instance of a FPU entity **322** having an entity name FPU and instantiation name FPU**0**. Within an entity description, it is common for the entity name to match the instantiation name when only one instance of that particular entity is placed at a given level of a simulation model hierarchy. However, this is not required as shown by entity **322** (instantiation name FPU**0**, entity name FPU).

[0059] Within instantiation **321a** of FXU entity **321**, single instance entities **325a** and **326a** of entity **A 325** and entity **B 326** respectively, are directly instantiated. Similarly instantiation **321b** of the same FXU entity contains instantiations **325b** and **326b** of entity **A 325** and entity **B 326** respectively. In a similar manner, instantiation **326a** and instantiation **326b** each directly instantiate a single instance of entity **C 327** as entities **327a** and **327b** respectively. The nesting of entities within other entities can continue to an arbitrary level of complexity provided that all entities instantiated, whether singly or multiply, have unique entity names and the instantiation names at any given level of the hierarchy are unique with

respect to one another. Each entity is constructed from one or more HDL files that contain the information necessary to describe the entity.

[0060] Associated with each entity instantiation is a so called “instantiation identifier”. The instantiation identifier for a given instantiation is a string consisting of the enclosing entity instantiation names proceeding from the top-level entity instantiation name. For example, the instantiation identifier of instantiation **327a** of entity **C 327** within instantiation **321a** of FXU entity **321** is “TOP.FXU0.B.C”. This identifier serves to uniquely identify each instantiation within a simulation model.

[0061] Referring now to **FIG. 3C**, there is depicted a flow diagram of a model build process which may be implemented in a preferred embodiment of the present invention. The process begins with one or more design entity HDL source code files **340** and, potentially, one or more design entity intermediate format files **345**, hereinafter referred to as “proto files” **345**, available from a previous run of an HDL compiler **342**. HDL compiler **342** processes HDL file(s) **340** beginning with the top level entity of a simulation model and proceeding in a recursive fashion through all HDL or proto file(s) describing a complete simulation model. For each of HDL files **340** during the compilation process, HDL compiler **342**, examines proto files **345** to determine if a previously compiled proto file is available and consistent. If such a file is available and consistent, HDL compiler **342** will not recompile that particular file, but will rather refer to an extant proto file. If no such proto file is available or the proto file is not consistent, HDL compiler **342** explicitly recompiles the HDL file **340** in question and creates a proto file **344**, for use in subsequent compilations. Such a process will be referred to hereinafter as “incremental compilation” and can greatly speed the process of creating a simulation executable model **348**. Incremental compilation is described in further detail hereinbelow. Once created by HDL compiler **342**, Proto files **344** are available to serve as proto files **345** in subsequent compilations.

[0062] In addition to proto files **344**, HDL compiler **342** also creates two sets of data structures, design entity proto data structures **341** and design entity instance data structures

343, in memory 44 of computer system 10. Design entity proto data structures 341 and design entity instance data structures 343, serve as a memory image of the contents of a simulation executable model 348. Data structures 341 and 343 are passed, via memory 44, to a model build tool 346 that processes data structures 341 and 343 into simulation executable model 348.

[0063] It will be assumed hereinafter that each entity is described by a single HDL file. Depending on convention or the particular HDL in which the current invention is practiced, this restriction may be required. However, in certain circumstances or for certain HDLs it is possible to describe an entity by utilizing more than one HDL file. Those skilled in the art will appreciate and understand the extensions necessary to practice the present invention if entities are permitted to be described by multiple HDL files. Furthermore, it will be assumed that there is a direct correspondence, for each entity, between the entity name and both of the following: the name of the HDL file representing the entity, and the name of the proto file for the entity.

[0064] In the following description, an HDL source code file corresponding to a given entity will be referred to by an entity name followed by ".vhdl". For example, the HDL source code file that describes top-level entity 320 will be referred to as TOP.vhdl. This labeling convention serves as a notational convenience only and should not be construed as limiting the applicability of the present invention to HDLs other than VHDL.

[0065] Returning to FIG. 3B, it can be seen that each entity may instantiate, either directly or indirectly, one or more other entities. For example, the FXU entity directly instantiates A entity 325 and B entity 326. Furthermore, B entity 326 directly instantiates C entity 327. Therefore, FXU entity 321 instantiates, directly or indirectly, A entity 325, B entity 326 and C entity 327. Those entities, that are directly or indirectly instantiated by another entity, will be referred to hereinafter as "descendants". The descendants of top level entity 320 are FXU entity 321, FPU entity 322, A entity 325, B entity 326, and C entity 327. It can be seen that each entity has a unique set of descendants and that each time an entity is instantiated, a

unique instance of the entity and its descendants is created. Within simulation model 329, FXU entity 321 is instantiated twice, FXU:FXU0 321a and FXU:FXU1 321b, by top-level entity 320. Each instantiation of FXU entity 321 creates a unique set of instances of the FXU, A, B, and C entities.

[0066] For each entity, it is possible to define what is referred to as a "bill-of-materials" or BOM. A BOM is a list of HDL files having date and time stamps of the entity itself and the entity's descendants. Referring again to FIG. 3C, the BOM for an entity is stored in proto file 344 after compilation of the entity. Therefore, when HDL compiler 342 compiles a particular HDL source code file among HDL files 340, a proto file 344 is generated that includes a BOM listing the HDL files 340 that constitute the entity and the entity's descendants, if any. The BOM also contains the date and time stamp for each of the HDL files referenced as each appeared on disk/tape 33 of computer system 10 when the HDL file was being compiled.

[0067] If any of the HDL files constituting an entity or the entity's descendants is subsequently changed, proto file 344 will be flagged as inconsistent and HDL compiler 342 will recompile HDL file 340 on a subsequent re-compilation as will be described in further detail below. For example, going back to FIG. 3B, the HDL files referenced by the BOM of FXU entity 321 are FXU.vhdl, A.vhdl, B.vhdl and C.vhdl, each with appropriate date and time stamps. The files referenced by the BOM of top-level entity 320 are TOP.vhdl, FXU.vhdl, A.vhdl, B.vhdl, C.vhdl, and FPU.vhdl with appropriate date and time stamps.

[0068] Returning to FIG. 3C, HDL compiler 342 creates an image of the structure of a simulation model in main memory 44 of computer system 10. This memory image is comprised of the following components: "proto" data structures 341 and "instance" data structures 343. A proto is a data structure that, for each entity in the model, contains information about the ports of the entity, the body contents of the entity, and a list of references to other entities directly instantiated by the entity (in what follows, the term "proto" will be utilized to refer to the in-memory data structure described above and the term

"proto file" will be utilized to describe intermediate format file(s) 344). Proto files 344 are therefore on-disk representations of the in-memory proto data structure produced by HDL compiler 342.

[0069] An instance data structure is a data structure that, for each instance of an entity within a model, contains the instance name for the instance, the name of the entity the instance refers to, and the port map information necessary to interconnect the entity with external signals. During compilation, each entity will have only one proto data structure, while, in the case of multiple instantiations of an entity, each entity may have one or more instance data structures.

[0070] In order to incrementally compile a model efficiently, HDL compiler 342 follows a recursive method of compilation in which successive entities of the model are considered and loaded from proto files 345 if such files are available and are consistent with the HDL source files constituting those entities and their descendants. For each entity that cannot be loaded from existing proto files 345, HDL compiler 342 recursively examines the descendants of the entity, loads those descendant entities available from proto file(s) 345 and creates, as needed, proto files 344 for those descendants that are inconsistent with proto files 345. Pseudocode for the main control loop of HDL compiler 342 is shown below (the line numbers to the right of the pseudocode are not a part of the pseudocode, but merely serve as a notational convenience).

```
process_HDL_file(file)                                5
{
    if (NOT proto_loaded(file)) {                      10
        if (exists_proto_file(file) AND check_bom(file)) { 15
            load_proto(file);
        } else {
            parse_HDL_file(file)                         20
            for (all instances in file) {
                process_HDL_file(instance);             25
            }
            create_proto(file);                        30
            write_proto_file(file);                   35
        }
    }
}
```

```
        }
    }
    create_instance(file):
}

```

65  
70  
75  
80

[0071] When compiler 342 is initially invoked, no proto data structures 341 or instance data structures 343 are present in memory 44 of computer system 10. The main control loop, routine process\_HDL\_file() (line 5), is invoked and passed the name of the top level entity by means of parameter "file". The algorithm first determines if a proto data structure for the current entity is present in memory 44 by means of routine proto\_loaded() (line 15). Note that the proto data structure for the top level entity will never be present in memory because the process starts without any proto data structures loaded into memory 44. If a matching proto data structure is present in memory 44, instance data structures for the current entity and the current entity's descendants, if any, are created as necessary in memory 44 by routine create\_instance() (line 75).

[0072] However, if a matching proto data structure is not present in memory 44, control passes to line 20 where routine exists\_proto\_file() examines proto files 345 to determine if a proto file exists for the entity. If and only if a matching proto file exists, routine check\_bom() is called to determine whether proto file 345 is consistent. In order to determine whether the proto file is consistent, the BOM for the proto file is examined. Routine check\_bom() examines each HDL source code file listed in the BOM to determine if the date or time stamps for the HDL source code file have changed or if the HDL source code file has been deleted. If either condition occurs for any file in the BOM, the proto file is inconsistent and routine check\_bom() fails. However, if check\_bom() is successful, control is passed to line 25 where routine load\_proto() loads the proto file and any descendant proto files into memory 44, thus creating proto data structures 341 for the current entity and the current entity's descendants, if any. The construction of process\_HDL\_file() ensures that once a proto file has been verified as consistent, all of its descendant proto files, if any, are also consistent.

[0073] If the proto file is either non-existent or is not consistent, control passes to line 35 where routine `parse_HDL_file()` loads the HDL source code file for the current entity. Routine `parse_HDL_file()` (line 35) examines the HDL source code file for syntactic correctness and determines which descendant entities, if any, are instantiated by the current entity. Lines 40, 45, and 50 constitute a loop in which the routine `process_HDL_file()` is recursively called to process the descendant entities that are called by the current entity. This process repeats recursively traversing all the descendants of the current entity in a depth-first fashion creating proto data structures 341 and proto data files 344 of all descendants of the current entity. Once the descendant entities are processed, control passes to line 55 where a new proto data structure is created for the current entity in memory 44 by routine `create_proto()`. Control then passes to line 60 where a new proto file 344, including an associated BOM, is written to disk 33 by routine `write_proto_file()`. Finally, control passes to line 75 where routine `create_instance()` creates instance data structures 343 for the current entity and any descendant entities as necessary. In this manner, `process_HDL_file()` (line 5) recursively processes the entire simulation model creating an in-memory image of the model consisting of proto data structures 341 and instance data structures 343.

[0074] With reference now to FIG. 3D there is depicted a block diagram representing compiled data structures which may be implemented in a preferred embodiment of the present invention. Memory 44 contains proto data structures 361, one for each of the entities referred to in simulation model 329. In addition, instantiations in simulation model 329 are represented by instance data structures 362. Instance data structures 362 are connected by means of pointers indicating the hierarchical nature of the instantiations of the entities within simulation model 329. Model build tool 346 in FIG. 3C processes the contents of memory 44 into memory data structures in order to produce simulation executable model 348.

[0075] In order to instrument simulation models, the present invention makes use of entities known as "instrumentation entities," which are in contrast to the entities constituting a design which are referred to herein as "design entities". As with design entities, instrumentation entities are described by one or more HDL source code files and consist of a number of

signal ports, a body section, and an entity name. In what follows, it will be assumed that an instrumentation entity is described by a single HDL file. Those skilled in the art will appreciate and understand extensions necessary to practice the current invention for an instrumentation entity that is described by multiple HDL files. Each instrumentation entity is associated with a specific design entity referred to hereinafter as the "target entity".

[0076] With reference now to **FIG. 4A**, there is illustrated a block diagram representation of an instrumentation entity **409**. Instrumentation entity **409** includes a number of input ports **400** that are connected to signals **401** within a target entity (not depicted in **FIG. 4A**). A body section **402** contains logic necessary to detect occurrences of specified conditions within the target entity and generate simulation model "events" with respect to signals **401**. Three distinct types of events may be generated: "count" events, "fail" events, and "harvest" events, each described below in turn. Body section **402** contains internal logic for detecting occurrences of conditions precipitating generation of these events. A set of multi-bit output ports **403**, **404**, and **405** are connected to external instrumentation logic (depicted in **FIG. 4B**) by means of external signals **406**, **407**, and **408**. Output ports **403**, **404**, and **405** thus provide the connection from the internal logic in body section **402** to the external instrumentation logic which is utilized to indicate the occurrence of count, failure and harvest events.

[0077] A failure event is a sequence of signal values that indicate a failure in the correct operation of the simulation model. Each instrumentation entity monitors the target entity for any desired number of failure events. Each occurrence of a failure event is assigned to a particular signal bit on output port **403**. Logic within body section **402** produces an active high pulse on a specified bit of signal **403** when a failure condition is detected. Such activation of signal **403** is defined as a failure event. This error indication is conveyed by means of external signal **406** to external instrumentation logic (depicted in **FIG. 4B** as external instrumentation logic block **420**), which flags the occurrence of the failure event.

[0078] A count event is a sequence of signal values that indicate the occurrence of an event within a simulation model for which it would be advantageous to maintain a count. Count events are utilized to monitor the frequency of occurrence of specific sequences within a simulation model. Each instrumentation entity can monitor the target entity for any desired number of count events. Each count event is assigned to a particular signal bit on output port **405**. Logic block **402** contains the logic necessary to detect the occurrence of the desired count events and produces an active high pulse on the specified bit of signal **405** when a count event is detected. This count indication is conveyed by means of external signal **408** to instrumentation logic, which contains counters utilized to record the number of occurrences of each count event.

[0079] The third event type, a harvest event, is a sequence of signal values that indicate the occurrence of a specific operative circumstance, which would be advantageous to be able to reproduce. When a harvest event occurs, a register within an external instrumentation logic block is loaded to indicate at what point within a simulation run the event occurred, and a flag is set to indicate the occurrence of the specific circumstance. The details of the simulation run can thus be saved in order to recreate the specific circumstance monitored by the harvest event. Logic block **402** contains the logic necessary to detect the harvest events.

[0080] Each instrumentation entity can detect any desired number of harvest events that are each assigned to a particular signal bit on output port **404**. Logic within block **402** produces an active high pulse on the specified bit of signal **404** when a harvest event is detected. This harvest event detection is conveyed by means of external signal **407** to external instrumentation logic that contains a register and flag for each harvest event. The register is utilized to record at which point in the simulation run the harvest event occurred, and the flag is utilized to indicate the occurrence.

[0081] With reference now to **FIG. 4B**, wherein is depicted a block diagram representation of simulation model **329** instrumented in accordance with the teachings of the present invention. As can be seen in **FIG. 4B**, an instance **410** and an instance **411** of an

instrumentation entity FXUCHK are utilized to monitor instances **321a** and **321b** of an FXU entity. For each FXU instantiations of **321a** and **321b**, an FXUCHK instantiation, **410** and **411** respectively, is automatically generated by the mechanism of the present invention. In a similar fashion, instrumentation entity FPUCHK **412** is instantiated to monitor FPU entity **322**.

[0082] As depicted in **FIG. 4B**, entity FXUCHK monitors a signals Q **372**, a signal R **376**, and a signal S **374** within each of instances **321a** and **321b** of the FXU entity. Signal Q **372**, is a signal within the instances **325a** and **325b** of descendant entity A. Likewise, signal S **374** is a signal within descendant entity C that resides within descendant entity **B**. Finally, signal R **376** occurs directly within FXU entity **321**. Although an instrumentation entity may monitor any signal within a target entity or the target entity's descendent entities, signals outside the target entity cannot be monitored.

[0083] Each instrumentation entity is connected by means of fail, count, and harvest signals to instrumentation logic block **420** containing logic for recording occurrences of each of the three event types. For the count events monitored in simulation model **329**, a set of counters **421** is utilized to count the number of occurrences of each count event. In a similar manner, a set of flags **424** is utilized to record the occurrence of failure events. Finally, a set of counters **422** and flags **423** are combined and utilized to record the point at which a harvest event occurs and its occurrence, respectively. In one embodiment of the present invention, a cycle number is captured and stored utilizing counters **422** and flags **423** to record a harvest event.

[0084] To facilitate instantiation and connection of instrumentation entities, instrumentation entity HDL source code files include a specialized comment section, hereinafter referred to as "instrumentation entity description", that indicates the target entity, the signals within the target entity to be monitored, and information specifying types of events to be monitored.

[0085] With reference now to **FIG. 4C**, there is illustrated an exemplary HDL file **440** that describes instrumentation entity FXUCHK depicted in **FIG. 4B**. HDL file **440** utilizes the syntax of the VHDL hardware description language. In the VHDL language, lines beginning with two dashes, “--”, are recognized by a compiler as being comments. The method and system of the present invention utilize comments of a non-conventional form to indicate information about an instrumentation entity. **FIG. 4C** depicts one embodiment of the present invention in which comments begin with two exclamation points in order to distinguish these comments from conventional comments in instrumentation HDL file **440**. It will be appreciated by those skilled in the art that the exemplary syntax utilized in **FIG. 4C** for the provision of unconventional comments is but one of many possible formats.

[0086] Within HDL file **440**, the I/O ports of a FXUCHK entity are declared in entity declaration **450**. Within entity declaration **450**, three input ports, S\_IN, Q\_IN, and R\_IN, respectively, are declared. Input ports, S\_IN, Q\_IN, and R\_IN, will be attached to signal S, 374, signal Q, 372, and signal R, 376 respectively as described below. Input port, CLOCK, is also declared and will be connected to a signal, CLOCK, within the FXU entity. In addition, three output ports: fails(0 to 1), counts(0 to 2), and harvests(0 to 1), are declared. These output ports provide failure, count, and harvest signals for two failure events, three count events, and two harvest events. The names of the output ports are fixed by convention in order to provide an efficient means for automatically connecting these signals to instrumentation logic block **420**.

[0087] A set of instrumentation entity descriptors **451** are utilized to provide information about the instrumentation entity. As illustrated in **FIG. 4C**, descriptor comments **451** may be categorized in a number of distinct sections: prologue and entity name declaration **452**, an input port map **453**, a set of failure message declarations **454**, a set of counter declarations **455**, a set of harvest declarations **456**, and an epilogue **457**.

[0088] The prologue and entity name **452** serve to indicate the name of the particular target entity that the instrumentation entity will monitor. Prologue and entity name declaration **452**

also serves as an indication that the instrumentation entity description has begun. Specifically, the comment “--!! Begin” within prologue and entity name **452**, indicates that the description of an instrumentation entity has begun. The comment “--!! Design Entity: FXU” identifies the target entity which, in HDL file **440**, is design entity FXU. This declaration serves to bind the instrumentation entity to the target entity.

[0089] Input port map **453** serves as a connection between the input ports of an instrumentation entity and the signals to be monitored within the target entity. The comments begin with comment “--!! Inputs” and end with comment “--!! End Inputs”. Between these comments, comments of the form “--!! inst\_ent\_port\_name => trgt\_ent\_signal\_name” are utilized, one for each input port of the instrumentation entity, to indicate connections between the instrumentation entity ports and the target entity signals. The inst\_ent\_port\_name is the name of the instrumentation entity port to be connected to the target entity signal. The trgt\_ent\_signal\_name is the name of the signal within the target entity that will be connected to the instrumentation entity port.

[0090] In some cases a signal to be monitored lies within a descendant of a target entity. This is the case for signal **S 374**, which is embedded within entity C which is a descendant of entity **B 326** and target FXU entity **321**. Input port map **453** includes an identification string for signal **S 374** which consists of the instance names of the entities within the target entity each separated by periods (“.”). This identification string is pre-pended to the signal name. The signal mapping comment within input port map **453** for signal **S 374** is therefore as follows:

--!! S\_IN => B.C.S

[0091] This syntax allows an instrumentation entity to connect to any signal within the target entity or the target entity’s descendant entities. A signal appearing on the top level of the target design entity, has no pre-pended entity names; and therefore, has the following signal mapping comment:

--!! R\_IN => R

[0092] For signals on the top level of the target entity, a special connection method is provided. If the signal to be connected to has the same name as its corresponding signal in the port map of the instrumentation entity, no input port mapping comment is required and the signal will be automatically connected if no such comment is present. In other words, if the input port mapping comment is of the form:

--!! signal => signal

where signal is a legal signal name without periods (“.”), then the input port mapping comment is not required and the system of the present invention will automatically make the connect. It is also possible to provide comments of the form given above to explicitly denote the signal connection. This mechanism is only operative for signals on the top level of the target entity.

[0093] Failure message declarations 454 begin with a comment of the form “--!! Fail Outputs;”, and end with a comment of the form “--!! End Fail Outputs;”. Each failure event output is associated with a unique event name and a failure message. This message may be output by the simulation run-time environment upon detecting a failure event. The unique failure event name is utilized to identify the specific failure event within the model. Each failure event signal may be declared by a comment of the form “--!! n: <eventname> “failure message;” where n is an integer denoting the failure event to which the message is associated, <eventname> is the unique failure event name, and “failure message” is the message associated with the particular failure event. One, and only one failure message declaration comment must be provided for each failure event monitored by the instrumentation entity.

[0094] Counter declaration comments 455 begin with a comment of the form “--!! Count Outputs;”, and end with a comment of the form “--!! End Count Outputs;”. Each count event output is associated with a unique variable name. This name is associated with a counter in

counter logic **421 FIG. 4B.** The variable name provides a means to identify and reference the particular counter associated with a particular count event. Thus, a comment of the form “`--!! n : <varname> qualifying_signal [+/-];`” is associated with each counter event output. Within this convention, n is an integer denoting which counter event in the instrumentation module is to be associated with a variable name “`varname`,” and `qualifying_signal` is the name of a signal within a target design entity utilized to determine when to sample the count event pulse as will be further described hereinbelow. The parameter “`qualifying_signal`” is followed by “`+/-`” to specify whether the qualifying signal will be a high active qualifying signal or a low active qualifying signal.

**[0095]** Harvest declarations **456** begin with a prologue comment of the form “`--!! Harvest Outputs;`” and end with a comment of the form “`--!! End Harvest Outputs;`”. Each harvest event output is associated with a unique event name and a message that may be output by the simulation runtime environment when a harvest event has occurred during a simulation run. Each harvest event signal is declared in the form “`--!! n: <eventname> "harvest message";`” where n is an integer denoting which harvest event the message is to be associated with, `<eventname>` is the unique harvest event name and “`harvest message`” is the message to be associated with the particular harvest event. One, and only one, harvest message declaration comment must be provided for each harvest event monitored by the instrumentation entity.

**[0096]** Harvest messages and event names, fail messages and event names, and counter variable names for a simulation model are included in a simulation executable model and lists of all the events within the model are produced in separate files at model build time. In this manner, each simulation model includes the information for each event monitored and a separate file containing this information for each event is available. Furthermore, as will be described below, the model build process names each event within the model (count, fail and harvest) model in such a manner as to insure that each event has a unique name with certain useful properties.

[0097] Finally, epilogue comment **457** consists of a single comment of the form “--!! End;”, indicating the end of descriptor comments **451**. The remainder of instrumentation entity HDL file **440** that follows the I/O declarations described above, is an entity body section **458**. In entity body section **458**, conventional HDL syntax is utilized to define internal instrumentation logic necessary to detect the various events on the input port signals and convey these events to the output port signals.

[0098] In addition to descriptor comments **451**, that are located in the HDL source code file for an instrumentation entity, an additional comment line is required in the target entity HDL file. A comment of the form “--!! Instrumentation: name.vhdl”, where name.vhdl is the name of the instrumentation entity HDL file, is added to the target entity HDL source code file. This comment provides a linkage between the instrumentation entity and its target entity. It is possible to have more than one such comment in a target entity when more than one instrumentation entity is associated with the target entity. These HDL file comments will hereinafter be referred to as “instrumentation entity instantiations”.

[0100] With reference now to **FIG. 4D**, there is depicted a model build process in accordance with the teachings of the present invention. In this model build process, instrumentation load tool **464** is utilized to alter the in-memory proto and instance data structures of a simulation model thereby adding instrumentation entities to the simulation model. Instrumentation load tool **464** utilizes descriptor comments **451** within instrumentation HDL files **461** to create instance data structures for the instrumentation entities within a simulation model.

[0101] The model build process of **FIG. 4D** begins with design entity HDL files **340** and, potentially, one or more design entity proto files **345** (available from a previous run of HDL compiler **462**), instrumentation entity HDL files **460**, and potentially, one or more instrumentation entity proto files **461** (available from a previous run of HDL compiler **462**). HDL compiler **462**, processes design entity HDL files **340**, and instrumentation entity HDL files **460** following an augmentation of algorithm process\_HDL\_file() that provides for

efficient incremental compilation of the design and instrumentation entities comprising a simulation model. HDL compiler 462 loads proto data structures from design entity proto files 345 and instrumentation entity protos files 460, if such proto files are available and consistent. If such proto files are not available or are not consistent, HDL compiler 462 compiles design entity HDL files 340 and instrumentation entity HDL files 460 in order to produce design entity proto files 344 and instrumentation entity proto files 468. (design entity proto files 344 and instrumentation entity proto files 468 are available to serve as design entity proto files 345 and instrumentation entity proto files 460 respectively for a subsequent run of HDL compiler 462).

[0102] In addition, HDL compiler 462 creates in-memory design proto data structures 463 and design instance data structures 465 for the design entities of a simulation model. HDL compiler 462 also creates in-memory instrumentation proto data structures 466 for the instrumentation entities of a simulation model.

[0103] In order to minimize processing overhead HDL compiler 462 neither reads nor processes descriptor comments 451. However, HDL compiler 462 does recognize instrumentation entity instantiation comments within target entity HDL files. As such, HDL compiler 462 cannot create instance data structures instrumentation entity data structures 467. The creation of instance data structures requires interconnection information contained within descriptor comments 451 not processed by HDL compiler 462. HDL compiler 462 does, however, create instrumentation proto data structures 466.

[0104] The in-memory design proto data structures 463, design instance data structures 465, and instrumentation entity proto data structures 466, are processed by instrumentation load tool 464. Instrumentation load tool 464 examines design entity proto data structures 463 and design entity instance data structures 465 to determine those design entities that are target entities. This examination is accomplished by utilizing a particular comment format as previously described.

[0105] All target entities that are loaded from design entity proto files 345 contain an instantiation for any associated instrumentation entity. Therefore, instrumentation load tool 464 merely creates an instance data structure 467 for any such instrumentation entity and passes, the unaltered design proto data structure 463 to instrumented design proto data structure 463a, and passes design instance data structure 465 to instrumented design instance data structure 465a.

[0106] If however, a target entity is loaded from design entity HDL files 340, rather than from design entity proto files 345, instrumentation load tool 464 must alter its design proto data structure 463 and its design instance data structure 465 to instantiate an associated instrumentation entity. An instrumented design proto data structure 463a and instrumented design instance data structure 465a are thereby produced. In addition, instrumentation load tool 464 creates an instrumentation instance data structure 467 for each instrumentation entity associated with the current design entity.

[0107] The design entity proto data structures 463 that are altered by instrumentation load tool 464 are saved to disk 33 of computer system 10 as design entity proto files 344. Design entity proto files 344, which may include references to instrumentation entities, are directly loaded by a subsequent compilation of a simulation model, thus saving processing by instrumentation load tool 464 on subsequent recompilations unless an alteration is made to a design entity or an associated instrumentation entity.

[0108] In order for HDL compiler 462 to determine if alterations were made to either a target design entity or the target design entity's associated instrumentation entities, the BOM of a target design entity is expanded to include the HDL files constituting the instrumentation entities. In this manner, HDL compiler 462 can determine, by inspection of the BOM for a given design entity, whether to recompile the design entity and the design entity's associated instrumentation entities or load these structures from proto files 345 and 461.

[0109] Finally, instrumentation load tool 464 creates a unique proto and instance data structure for instrumentation logic block 420 and connects the fail, harvest, and count event signals from each instrumentation entity instantiation to instrumentation logic block 420. Model build tool 446 processes in-memory proto and instance data structures 463a, 465a, 467, 466 to produce instrumented simulation executable model 480.

[0110] In HDL compiler 462, algorithm process\_HDL\_file() is augmented to allow for the incremental compilation of design and instrumentation entities. A pseudocode implementation of a main control loop of HDL compiler 462 is shown below:

```

process_HDL_file2(file,design_flag)      5
{
    if (NOT proto_loaded(file)) {      10
        if (exists_proto_file(file) AND check_bom(file)) {  15
            load_proto(file);
        }
    }else {                          20
        parse_HDL_file(file)          25
        for (all instances in file) { 30
            process_HDL_file2(instance, design_flag);
        }
        if (design_flag=TRUE) {        35
            for (all instrumentation instances in file){ 40
                process_HDL_file2(instance, FALSE);       45
            }
        }
    }
    if (design_flag = TRUE) {           50
        create_proto(file);           55
        write_proto_file(file);
    }
}
if (design_flag = TRUE) {                60
    create_instance(file);             65
}
}

```

[0111] Algorithm process\_HDL\_file2() is an augmentation to process\_HDL\_file() of HDL compiler 342 in order to support the creation of instrumented simulation models. The algorithm is invoked with the name of the top level design entity passed through parameter file and a flag indicating whether the entity being processed is a design entity or an instrumentation entity passed through parameter design\_flag (design\_flag = TRUE for design

entities and FALSE for instrumentation entities). Algorithm process\_HDL\_file2() (line 5) first checks, by means of routine proto\_loaded() (line 15), if the proto for the current entity is already present in memory 44. If so, processing passes to line 105. Otherwise, control is passed to line 20 and 25 where disk 33 of computer system 10 is examined to determine if proto files for the entity and its descendants (including instrumentation entities, if any) exist and are consistent. If so, the appropriate proto files are loaded from disk 10 by routine load\_proto() (line 25) creating proto data structures, as necessary, in memory 44 for the current entity and the current entity's descendants including instrumentation entities.

[0112] If the proto file is unavailable or inconsistent, control passes to line 35 where the current entity HDL file is parsed. For any entities instantiated within the current entity, lines 40 to 55 recursively call process\_HDL\_file2() (line 5) in order to process these descendants of the current entity. Control then passes to line 55 where the design\_flag parameter is examined to determine if the current entity being processed is a design entity or an instrumentation entity. If the current entity is an instrumentation entity, control passes to line 80. Otherwise, the current entity is a design entity and lines 60 to 70 recursively call process\_HDL\_file2() (line 5) to process any instrumentation entities instantiated by means of instrumentation instantiation comments. It should be noted that algorithm process\_HDL\_file2() (line 5) does not allow for instrumentation entities to monitor instrumentation entities. Any instrumentation entity instantiation comments within an instrumentation entity are ignored. Control then passes to line 80 where proto data structures are created in memory 44 as needed for the current entity and any instrumentation entities. Control then passes to line 90 where the newly created proto data structures are written, as needed to disk 33 of computer system 10.

[0113] Control finally passes to line 105 and 110 where, if the current entity is a design entity, instance data structures are created as needed for the current entity and the current entity's descendants. If the current entity is an instrumentation entity, routine create\_instance() (line 110) is not called. Instrumentation load tool 464 is utilized to create the in-memory instance data structures for instrumentation entities.

[0114] It will be apparent to those skilled in the art that HDL compiler 462 provides for an efficient incremental compilation of design and instrumentation entities. It should also be noted that the above description is but one of many possible means for accomplishing an incremental compilation of instrumentation entities. In particular, although many other options also exist, much, if not all, of the functionality of instrumentation load tool 464 can be merged into HDL compiler 462.

[0115] With reference now to FIG. 4E wherein is shown a depiction of memory 44 at the completion of compilation of simulation model 329 with instrumentation entities FXUCHK and FPUCHK. Memory 44 contains proto data structures 481, one for each of the design and instrumentation entities referred to in simulation model 329. In addition, design and instrumentation instances in simulation model 329 are represented by instance data structures 482. The instance data structures are connected by means of pointers indicating the hierarchical nature of the instantiations of the design and instrumentation entities within simulation model 329.

[0116] With reference now to FIG. 5A, failure flags 424 of instrumentation logic block 420 are depicted in greater detail. Failure flags 424 consist of registers 500a-500n utilized to accept and store an indication of the occurrence of a failure event. In what follows, the operation of a single failure flag for a particular failure event 502 will be discussed. The operation of all failure flags is similar.

[0117] Register 500a holds a value that represents whether a failure event 502 has occurred or not. Register 500a is initially set to a value of '0' by the simulation run-time environment at the beginning of a simulation run. When failure event 502, if enabled at register 507a, occurs, register 500a is set to a value of a logical '1', thereby indicating the occurrence of a failure event. Register 500a is driven by logical OR gate 501. Logical OR gate 501 performs a logical OR of the output of register 500a and a qualified failure signal 503 to create the next cycle value for register 500a. In this manner, once register 500a is set to a

logical ‘1’ by the occurrence of an enabled failure event, register **500a** maintains the value of a logical ‘1’ until reset by the simulation runtime environment. Likewise, register **500a** maintains a value of ‘0’ from the beginning of the simulation run until the occurrence of the failure event, if enabled.

[0118] Qualified failure signal **503** is driven by logical AND gate **505**. Logical AND gate **505** produces, on qualified failure signal **503**, the logical AND of failure signal **506** and the logical NOT of register **507a**. Register **507a** serves as an enabling control for qualified failure signal **503**. If register **507a** contains a value of ‘0’, logical AND gate **505** will pass failure event signal **506** unaltered to qualified failure signal **503**. In this manner, the monitoring of the failure event is enabled. Registers **507a-507n** are set, by default, to a value of ‘0’. However, if register **507a** contains a value of a logical ‘1’, qualified failure signal **503** will remain at a value of ‘0’ irrespective of the value of failure event signal **506**, thereby disabling the monitoring of failure event **502**. In this manner, register **508**, consisting of registers **507a-507n**, can mask the occurrence of any subset of failure events in the overall simulation model from registers **500a-500n**.

[0119] To efficiently implement the ability to selectively disable the monitoring of failure events, the simulation run-time environment includes a function that allows a user to disable monitoring of a specific failure event for a given instrumentation entity. This function will automatically set the appropriate registers among registers **507a-507n** within register **508** to disable the monitoring of a particular failure event for every instance of the instrumentation entity within the overall simulation model. Instrumentation load tool **464** and model build tool **446** encode sufficient information within instrumented simulation executable model **480** to determine which failure bits within register **508** correspond to which instrumentation entities.

[0120] The ability to selectively disable monitoring of failure events is of particular use in large batch-simulation environments. Typically, in such an environment, a large number of general purpose computers, running software or hardware simulators, are dedicated to

automatically running a large number of simulation runs. If a simulation model with a faulty instrumentation entity that incorrectly indicates failure events is run in such an environment, a large number of erroneous failures will be generated causing lost time. By selectively disabling failure events within instrumentation entities, the present invention allows simulation to continue while only disabling erroneous failure signals rather than having to disable all failure monitoring. This option is particularly useful when the process of correcting a faulty instrumentation entity and creating a new simulation model is substantially time consuming. The present invention also provides similar enabling and disabling structures for the harvest and count events within a model.

[0121] Logical OR gate **512** is utilized to produce a signal **511** that indicates whether any failure event within the model has occurred. This signal is utilized to allow hardware simulators to efficiently simulate simulation models that have been instrumented according to the teachings of the present invention.

[0122] With reference now to **FIG. 5B** there is illustrated in greater detail, features of the present invention utilized to support efficient execution of an instrumented simulation model on a hardware simulator. It should be noted that for most hardware simulators, the operation of polling a facility within a simulation model during a simulation run is often a time consuming operation. In fact, if facilities must be polled every cycle, it is often the case that as much, if not considerably more, time is spent polling a simulation model for results rather than running the actual simulation. As such, it is advantageous when using a hardware simulator to avoid polling facilities within the model during a simulation run. In addition, many hardware simulators provide a facility that instructs the hardware simulator to run a simulation without interruption until a specific signal within the simulation model attains a specific value. This facility usually results in the highest performance for a simulation run on a hardware simulator.

[0123] In order to execute simulation model **520** on a hardware simulator, a termination signal **513**, is typically utilized as a means to avoid having to poll the model after each cycle.

Typically, a hardware simulator will cycle simulation model **520** until signal **513** is asserted to a logical '1'. The assertion of termination signal **513** to a logical '1' indicates that a simulation run has finished. Without termination signal **513**, it would be necessary to directly poll facilities within simulation model **520** to determine when a simulation run is completed.

[0124] To efficiently locate and diagnose problems in simulation model **520**, it is advantageous to allow a simulation run to be stopped immediately whenever a failure event occurs during simulation of simulation model **520** (harvest events and count events are typically only polled at the end of a simulation run). This allows a user to easily locate the failure event within the simulation run, thereby facilitating debugging of the failure. In order to allow simulation models that have been instrumented according to the teachings of the present invention to efficiently execute on a hardware simulator, a comment of the form "--!! Model Done: signalname" is placed within the HDL source code file for the top-level entity of the simulation model where signalname is the name of termination signal **513** within the simulation model. This comment is only utilized if present in the HDL file for the top-level entity. If such a comment is present in the HDL source code file for the top-level entity, a logical OR gate **515** will automatically be included within the simulation model. Logical OR gate **515** produces the logical OR of signals **511** and **513** on signal **516**. Signal **516** is therefore asserted to a logical '1' whenever the simulation run has completed (signal **513** high) or a failure event has occurred (signal **511** high). Consequently, by executing simulation model **520** in a hardware simulator until signal **516** is asserted to a value of a logical '1', the instrumentation for simulation model **520** can be combined and utilized along with existing simulation termination techniques in a seamless manner. In the alternative, if the comment indicating the name of termination signal **513** is not present, logical OR gate **515** is not included in the model and signal **511** is directly connected to signal **516**. The name of signal **516** is fixed to a particular name by convention.

[0125] In many simulators, the passage of time within the simulated model is modeled on a cycle-to-cycle basis. That is to say, time is considered to pass in units known as cycles. A

cycle is delineated by the occurrence of a clock signal within a simulation model that regulates the updating of storage elements within the design. These simulators are commonly known as "cycle simulators". A cycle simulator models a digital design by repeatedly propagating the values contained within storage elements through interconnecting logic that lies between storage elements without specific regard for the physical timing of this propagation, to produce next cycle values within the storage elements. In such simulators, a primitive storage element, hereinafter referred to as a "simulator latch", is utilized to model the storage elements within a digital design. One simulator cycle therefore consists of propagating the current values of the simulator latches through the interconnecting logic between storage elements and updating the simulator latches with the next cycle value.

[0126] In many circumstances, however, it is not possible to utilize a single simulator latch to directly model the storage elements within a design. Many common storage elements utilized within digital designs often require more than one simulator latch. For example, so called master-slave flip-flops are generally modeled utilizing two simulator latches to accurately simulate the behavior of such storage elements. In order to efficiently model storage elements, a designer will typically refer to a library that contains storage element simulation models for use in a design. These design storage elements are modeled by one or more simulator latches. Storage elements comprised of one or more simulator latches that are implemented within a design will be referred to hereinbelow as "design latches".

[0127] As a consequence of utilizing multiple simulator latches to model a design latch, the process of propagating the input of a design latch to its output, which constitutes a design cycle, often requires more than one simulator cycle. A single design cycle is thus defined as comprising the number of simulator cycles required to propagate a set of values from one set of storage elements to the next.

[0128] In other circumstances, a simulation model may consist of distinct portions that are clocked at differing frequencies. For example, a microprocessor core connected to a bus interface unit, may operate at a higher frequency and than the bus interface unit. Under these

circumstances, the higher frequency portion of the design will require one or more simulator cycles, say N cycles, to simulate a single design cycle. The lower frequency portion of the design will require a multiple of N simulator cycles in order to simulate a design cycle for the lower frequency portion. This multiple is equal to the ratio of the frequency of the higher speed design portion to the frequency of the lower speed design portion. It is often the case that certain portions of the logic can be run at a number of differing frequencies that are selectable at the beginning of a simulation run. Such logic, with a run-time selectable frequency of operation, presents unique challenges for monitoring count events.

[0129] With reference now to FIG. 6A, there is depicted a gate level representation of exemplary logic for one counter of counters 421 within instrumentation logic block 420 depicted in FIG. 4B. Each counter 421 is represented by a multi-bit simulator latch 600. Simulator latch 600 is initialized by the simulation runtime environment to a value of zero at the beginning of a simulation run. Simulator latch 600 is updated every simulator cycle and is driven by multiplexor 601. Multiplexor 601, controlled by selector signal 602, selects between signal 613, the current value of simulator latch 600, and signal 605, the current value of simulator latch 600 incremented by 1 by incrementor 604, to serve as the next cycle value for simulator latch 600. By selecting signal 605, multiplexor 601 causes the counter value within simulator latch 600 to be incremented when a count event occurs. It should be noted, however, that simulator latch 600 is updated every simulator cycle irrespective of the number of simulator cycles that correspond to a design cycle for the logic being monitored by a counting instrument. Logical AND gate 606 and simulator latch 607 serve to disable the monitoring of count event signal 609 in a manner similar to that described above for the disabling of failure events. Signal 608 is count event signal 609 further qualified by signal 610 by means of logical AND gate 611.

[0130] Signal 610 insures that simulator latch 600 will be incremented, if count event signal 609 is active, only once per design cycle for the logic being monitored by a counting instrument irrespective of the number of simulation cycles utilized to model the design cycle. This clocking normalization is necessary to ensure that the event counts recorded in counters

**421** correspond directly to the number of design cycles the event occurred in and not the number of simulator cycles the event occurred in. For example if an event occurs in two design cycles where design cycle require four simulators cycles, it is preferable to have the event counter reflect a value of two rather than a value of eight as would occur if the counter were allowed to update in every simulator cycle.

[0131] Furthermore, if the count event being monitored is within a portion of the logic with a run-time selectable frequency of operation, it is useful to have the count registers reflect the number of occurrences of the event in terms of design cycles. For example, consider a circumstance where a count event occurs twice during two different simulation runs. In the first run, assume that four simulator cycles are needed to represent each design cycle. Further assume in the second run that twelve simulator cycles are necessary to represent each design cycle. Without a clocking normalization mechanism, the first run would indicate that the event occurred eight times (two occurrences times four simulator cycles per occurrence) and the second run would indicate that the event occurred twenty-four times (two occurrences times twelve simulator cycles per occurrence) when in fact the event actually only occurred twice in both simulation runs. Therefore, it would be advantageous to limit the updating of counters **421** such that each counter is only updated once per design cycle irrespective of the number of simulator cycles, possibly variable at run-time, needed to represent a design cycle.

[0132] In simulation models in which multiple simulator cycles are utilized to represent a single design cycle, explicit clocking signals are utilized within the model to control the updating of the various design storage elements. These clocking signals specify in which simulator cycles the simulator latches representing design storage elements are allowed to update. A clocking signal is asserted high for some contiguous number of simulator cycles either at the beginning or end of the design cycle and asserted low for the remaining simulator cycles within the design cycle. If the clocking signal is asserted high during the beginning of the design cycle, the clock is referred to as a "high-active" clock and, likewise,

if the clocking signal is asserted low during the beginning of the design cycle, the clock is referred to as a “low-active” clock.

[0133] Each count event signal has an associated qualifying signal as specified by counter declaration comments 455 as described above. Typically, these qualifying signals are connected to the clocking signals within the design responsible for updating the storage elements within the portion of logic monitored by the count event. The qualifying signal for the count event for simulator latch 600, qualifying signal 612, is depicted as a high-active qualifier signal. Qualifying signal 612 is processed by simulator latch 613 and logical AND gate 614, to produce signal 610 which is active high for one and only one simulator cycle within the design cycle delineated by qualifying signal 612.

[0134] Turning now to FIG. 6B there is illustrated a simplified timing diagram that demonstrates operation of simulator latch 613 and logical AND gate 614 assuming clocking qualifying signal 612 is a high active clocking signal of fifty percent duty cycle for a design cycle that occurs over a 10- simulation cycle period. Signal 615, the output of simulator latch 613, is qualifying signal 612 delayed by one simulator cycle. Signal 615 is inverted and logically ANDed with qualifying signal 612 to produce signal 610, a high-active pulse that is asserted for the first simulator cycle of the design cycle. In a similar fashion, if the qualifying clock signal is low active, qualifying signal 612 would be inverted and signal 615 would be uninverted by logical AND gate 614. This would produce a single simulator cycle active high pulse during the first simulator cycle of the design cycle. Qualifying signal 610, by qualifying count event signal 609 by means of logical AND gate 611, insures that counter 600 is incremented only once per design cycle irrespective of the number of simulator cycles utilized to represent a design cycle.

[0135] In contrast to cycle simulators, another class of simulators known as “event-driven” simulators is commonly utilized. In an event driven simulator, time is modeled in a more continuous manner. Each rising or falling edge of a signal or storage element within a design is modeled with specific regard to the physical time at which the signal transition occurred.

In such simulators, the simulator latches operate in a slightly different manner than for a cycle based simulator. A simulator latch in an event driven simulator is controlled directly by a clocking signal. A new value is loaded into the simulator latch on either the rising or falling edge of the clocking signal (called a “positive-edge triggered” latch and a “negative-edge triggered” latch respectively). To practice the current invention within an event driven simulator, latch 613 and logical gates 614 and 611 are unnecessary. Rather, counter latch 600 is replaced by a positive or negative edge triggered simulator latch based on the polarity of qualifying signal 612. Qualifying signal 612 is connected directly to simulator latch 600 and directly controls the updates of counter latch 600 insuring that the latch is updated only once per design cycle.

[0136] Returning to FIG. 6A, incrementor 604 represents but one possible mechanism that may be utilized to implement the next logic state for a given counter within the present invention. As depicted in FIG. 6A, incrementor 604 ensures that counters 421 within a model are cycled through a series of values whose binary patterns correspond to the customary representation of non-negative integers. In one embodiment of the present invention, incrementor 604 is comprised of an adder that increments the current value of counter 600 by a unit value each time signal 605 is selected by selector signal 602. This exemplary implementation provides for convenience of decoding the value of counter 600 at the termination of a simulation run, but does so at a cost in overhead that is not acceptable in many simulators.

[0137] For software simulators, one of two basic approaches may be utilized to model an incrementor, such as incrementor 604. In the first approach, the incrementor is modeled directly by an ADD or INCREMENT instruction in the simulation execution model. When incrementors are modeled directly as a single instruction within the simulation execution model, the use of incrementor 604 provides for efficient counters within a simulation execution model.

[0138] However, many software simulators and virtually all hardware simulators model incrementor functions as a set of gates that are replicated essentially without change at each bit position of the counter. Within a software simulator, these gates must be translated into a sequence of instructions. In a hardware simulator, these gates are explicitly replicated for each counter as individual gates. Due to implementation or structural limitations, many software simulators are incapable of modeling an incrementor in any other manner than as a set of gates. Clearly, for these software simulators that must model incrementors as a number of gates and therefore as a sequence of instructions, a performance loss will result over those software simulators that model incrementors as a single increment or add instruction. Likewise, for hardware simulators, the number of gates required for each adder, which must be modeled directly by gates within the hardware simulator, can prove to be a significant burden.

[0139] The method and system of the present invention alleviate these difficulties by implementing a linear feedback shift register as the counting means within counting instrumentation. As explained below, appropriate configuration and utilization of such a liner feedback shift register results in an efficient method of incrementing a counter that avoids the overhead associated with incrementor 604.

[0140] With reference now to FIG. 7, there is depicted a linear feedback shift register (LFSR) counter 700 consisting of a shift register 704 and “exclusive NOR” (XNOR) gate 706. Various methods of constructing LFSRs are known to those skilled in the art. As illustrated in FIG. 7, LFSR counter 700 includes a modified shift register 704 that may replace register 600 and incrementor 604 of FIG. 6A. LFSR counter 700 also includes multiplexor 601 (replicated bit-by-bit within LFSR 704), which provides feedback paths 616. Feedback path 616 provides a means for shift register 704 to maintain its current value during those simulator cycles in which no count pulse trigger (signal 602) is received. For hardware and software design simulators in which, for logistical or other reasons, incrementation of counters must be accomplished utilizing a set of gates for each counter, shift register 704 replaces register 600 within the counter logic depicted in FIG. 6A. The

need for incrementor 604 is thus eliminated and is replaced by XNOR gate 706. In this manner, register 600 and incrementor 604 are replaced utilizing a more efficient logic structure having substantially reduced overhead. Counters 421 of FIG. 4B, will therefore consist of LFSR-based configurations such as LFSR counter 700 whose values can be decoded at the end of a simulation run to reveal their corresponding integral values.

[0141] Shift register 704 can be of any desired length. In a preferred embodiment, shift register 704 is a 22 bit register, although larger or smaller registers may be employed. Shift register 704 consists of latches 718 arranged in a serial fashion such that a given latch's output is utilized as input to the next latch 718 within shift register 704. In addition, a select subset of latches 718 within shift register 704 have their outputs sourced to XNOR gate 706. XNOR gate 706 is utilized to provide an input for the first latch within shift register 704.

[0142] The LFSR is a logic structure that, when properly configured, will sequence through all possible bit patterns with the exception of the all-ones pattern (it is possible to construct LFSRs which exclude the all-zeros pattern or LFSRs that cycle through all possible bit patterns). For example, in a 22 bit LFSR, bits 1 and 22 may be selected for inputs to XNOR gate 706 to provide a sequence of bit patterns in shift register 704 which traverses every possible permutation with the exception of the all-ones pattern. Shift register 704 must be loaded with an initial value that is not the all ones pattern. This may be accomplished automatically by initializing all latches to a binary zero value within the simulator, or by utilizing the control program that drives the simulator to explicitly set these latches to binary zeros.

[0143] After initialization, the numeric pattern held by bit positions 718 of shift register 704 will cycle through a specific and predictable pattern in a repeating fashion. That is to say, for any given bit pattern present in shift register 704, there is a specific, unique pattern the shift register will subsequently assume upon being shifted and therefore, the sequence of patterns through which the shift register cycles is fixed and repeats in a predictable manner. Due to these properties, LFSR counter 700 can be utilized as a counting means within for the

instrumentation detection means previously described. By assigning the value of “zero” to a pre-selected starting value (say the all zeros pattern for shift register **704**), the value of “one” to the next bit pattern formed by shifting the LFSR, and so on, the LFSR can serve as a counter. To be useful as a counter, the bit patterns within shift register **704** must be converted back to their corresponding integer values. This is easily accomplished for LFSRs with a small number of bits (less than **25** bits) by means of a lookup table consisting of an array of values, where the index of the array corresponds to the LFSR bit pattern value and the entry in the array is the decoded integer value for the LFSR. For LFSRs with a larger number of bits, software decoding techniques can be utilized to decode the LFSR value by simulating the operation of the LFSR.

[0144] As illustrated in **FIG. 7**, the logic necessary to implement LFSR counter **700** consists of the single XNOR gate **706** with two feedback inputs. While the number of required feedback gates and inputs thereto may vary in proportion to different possible lengths of an LFSR, in general, for typical LFSRs (less than **200** bits), only one XNOR gate with a relatively small number of inputs (less than **5** bits) is required. This is in marked contrast to the several logic gates per bit required for conventional incrementors. Therefore, significant savings in counter overhead can be achieved by substituting LFSR-based counter **700** for the incrementor structure depicted in **FIG. 6A**, especially for simulators that model incrementors utilizing logic gate based representations.

[0145] While the above described system and method provides a practical means of instrumenting simulation models, in certain circumstances additional techniques may be used in order to enhance the ease with which a user may instrument a simulation model. In design, it often occurs that there are common design or instrumentation logic constructs that are often repeated and possess a regular structure.

[0146] By utilizing knowledge of the regular structure of these design and instrumentation logic constructs, it is often possible to define a syntax that describes the instrumentation logic with considerably greater efficiency than would be possible utilizing a conventional HDL

construct. By utilizing this syntax as an unconventional HDL comment within a design VHDL file, it is possible to create instrumentation entities with considerably greater ease and efficiency.

[0147] Such comments within a design entity will be referred to hereinbelow as an embedded instrumentation entity comment while the instrumentation logic created by such a comment will be referred to as an embedded instrumentation entity.

[0148] A common logic design construct is the so-called “finite state machine”. A finite state machine typically consists of a number of storage elements to maintain the “state” of the state machine and combinatorial logic that produces the next state of the state machine and its outputs. These constructs occur with great frequency in typical logic designs and it is advantageous to be able to efficiently instrument these constructs.

[0149] A typical set of count and failure events for a finite state machine includes counting the number of times a state machine cycles from a given current state to some next state, counting the number of functional cycles the state machine spends in each state, ensuring that the state machine does not enter an illegal state, and ensuring that the state machine does not proceed from a current given state to an illegal next state. This list of events is but one of many possible sets of events that can be used to characterize a finite state machine and is used in an illustrative manner only.

[0150] With reference now to FIG. 8A there is depicted a representation of an exemplary state machine **800**. Exemplary state machine **800** consists of five states, labeled S<sub>0</sub>, S<sub>1</sub>, S<sub>2</sub>, S<sub>3</sub>, and S<sub>4</sub> respectively, and nine legal state transitions between these states. In what follows, it is assumed that state machine **800** consists of three latches and a set of combinatorial logic to produce the next state function. It is further assumed that the states are encoded into the three latches following the usual and customary encoding for integers. That is to say, state S<sub>0</sub> gets an encoding of 000<sub>bin</sub>, state S<sub>1</sub> gets an encoding of 001<sub>bin</sub>, state S<sub>2</sub> gets an encoding of 010<sub>bin</sub>, and so on.

[0151] With reference now to **FIG. 8B** there is shown an exemplary design entity **850** referred to as entity FSM with instance name FSM, which contains one instance of state machine **800**. Furthermore, a signal output **801**, “fsm\_state(0 to 2)” contains a three bit signal directly connected to the outputs of the three storage elements comprising the state elements of state machine **800**. A signal input **802**, fsm\_clock, applies a clocking signal that controls the storage elements for state machine **800**.

[0152] In order to instrument state machine **800**, it would conventionally be necessary to create an instrumentation entity VHDL file containing the logic necessary to detect the desired state machine events and pass them through to count and fail events. Such an instrumentation entity file with appropriate instrumentation entity descriptor comments would typically require substantially more lines of code than the HDL description of the state machine itself. Such a circumstance is undesirable. However, in the case of a regular logic structure such as a finite state machine, it is possible to define a brief syntax that characterizes the finite state machine without resorting to a separate instrumentation VHDL entity.

[0153] With reference now to **FIG. 8C** there is illustrated an exemplary HDL file **860** for generating design entity **850** with an embedded instrumentation entity for monitoring the behavior of FSM **800**. Specifically, an embedded instrumentation entity comment **852** is illustrated. As depicted in **FIG. 8C**, embedded instrumentation entity comment **852** comprises a number of distinct sections including: a prologue and embedded instrumentation name declaration **853**, a state machine clock declaration **859**, a state element declaration **854**, a state naming declaration **855**, a state element encoding declaration **856**, a state machine arc declaration **857**, and an epilogue **858**.

[0154] Prologue and embedded instrumentation entity name declaration comment **853** serves to declare a name that is associated with this embedded instrumentation entity. This

comment line also serves to delineate the beginning of an embedded instrumentation entity comment sequence.

[0155] As further depicted in FIG. 8C, declaration comment 853 assumes a non-conventional syntax of the form: “--!! Embedded TYPE: name”, wherein “--!! Embedded” serves to declare an embedded instrumentation entity, “TYPE” declares the type of the embedded instrumentation entity – FSM in this case, and “name” is the name associated with this embedded instrumentation entity.

[0156] State machine clock declaration comment 859 is utilized to define a signal that is the clocking control for the finite state machine.

[0157] State element declaration comment 854 is utilized to specify the state-machine state storage elements. This comment declares the storage elements or signal names that constitute the state-machine state. In state machine 800, the signals fsm\_state(0 to 2) constitute the state machine state information.

[0158] State naming declaration comment 855 is utilized to declare labels to associate with various states of the given state machine. These labels are utilized in state machine arc declaration comment 857 when defining the legal state transitions within the given state machine.

[0159] State element encoding declaration comment 856 is utilized to define a correspondence between the state machine labels defined by state naming declaration comment 855 and the facilities declared by state element declaration comment 854. In the example shown, the labels of comment 855 are associated by position with the encodings given in comment 856 (i.e., the state labeled “S0” has the encoding 000<sub>bin</sub>, the state labeled “S1” has the encoding 001<sub>bin</sub>, etc.).

[0160] State-machine arc declaration comment **857** defines the legal state transitions within the state machine. The various transitions of the state machine are given by terms of the form “X => Y” where X and Y are state machine state labels given by comment **855** and X represents a previous state machine state and Y a subsequent state machine state.

[0161] Epilogue comment **858** serves to close the embedded instrumentation entity comment. The specific syntax and nature of the comments between the prologue and embedded instrumentation name declaration and the epilogue will vary with the specific needs of the type of embedded instrumentation entity being declared.

[0162] Embedded instrumentation entity comment **852** is inserted within the VHDL file of the design entity that contains the finite state machine in question. The embedding of instrumentation for finite state machine **800** is made possible by the non-conventional comment syntax illustrated in **FIG. 8C** and is substantially more concise than a conventional HDL instrumentation entity suitable for accomplishing the same function.

[0163] Utilizing such embedded non-conventional comments, the system of the present invention creates an instrumentation entity, as described below, for instrumenting the state machine without the need to resort to creating a separate HDL file instrumentation entity.

[0164] To support compilation and creation of embedded instrumentation entities, the previously described compilation process of **FIG. 4D** is enhanced as described herein. First, HDL compiler **462** is altered to recognize the presence of embedded instrumentation entity comments. If, during compilation of a design HDL file, and subject to the constraints described above for incremental compilation, HDL compiler **462** detects one or more embedded instrumentation entity comments within the source code file, HDL compiler **462** places a special marker into design entity proto data structure **463**.

[0165] When instrumentation load tool **464** is passed control, proto data structures **463** are searched in order to locate the special marker placed by HDL compiler **462** indicating

embedded instrumentation entity comments. Such protos represent the design HDL files with embedded instrumentation entities that have been re-compiled in the current compilation cycle.

[0166] When instrumentation load tool 464 locates a proto data structure 463 with the special marker, the corresponding VHDL source code file for the design entity is opened and parsed to locate the one or more embedded instrumentation entity comments. For each of these comments, instrumentation load tool 464 creates a specially named proto data structure 463a, and further generates a corresponding instance data structure 465a that is instantiated within the design entity. In addition, instrumentation load tool 464 removes the special marker inserted by HDL compiler 462 to prevent unnecessary re-instrumentation of the design proto on subsequent re-compiles.

[0167] Within these created embedded instrumentation entity protos, instrumentation load tool 464 directly creates the necessary instrumentation logic required by the embedded instrumentation entity without the need for a VHDL file to specify this instrumentation and connects this logic to instrumentation logic block 420 of FIG. 4D. The updated design proto along with the embedded instrumentation entity proto and instance data structure are saved to disk and serve as inputs to subsequent compiles, removing the need to produce embedded instrumentation entities on subsequent recompiles.

[0168] With reference now to FIG. 9, design entity 850 is shown instrumented with embedded instrumentation entity 900. Embedded instrumentation entity 900 is created as a proto instantiated within design entity 850 wherein the embedded non-conventional instrumentation entity comment occurs. The embedded instrumentation entity thus may be replicated automatically within an overall design wherever the specific design entity is instantiated.

[0169] Embedded instrumentation entity 900 is named in a unique manner based on the name associated with the embedded instrumentation entity by the prologue and embedded

instrumentation name declaration comment. This name is pre-pended with a special character (shown as a “\$” in **FIG. 9**) that is not a recognized naming convention for the platform HDL. In this manner, the names of the embedded instrumentation entities cannot conflict with the names of any other design or standard instrumentation entities.

[0170] Furthermore, the names associated with the various events defined by the embedded instrumentation entity (the “varname” for the count events, for example) are also derived in a fixed manner from the name associated with the embedded instrumentation entity. The user is required to ensure that the names of embedded instrumentation entity events do not conflict with the names of standard instrumentation entity events and further than the names of the embedded instrumentation entities within a given design do not themselves conflict.

[0171] It should also be noted that if a design entity contains more than one embedded instrumentation entity, the embedding process described with reference to **FIG. 8B** and **FIG. 9** is simply repeated for each such instrumentation entity. In addition, since the protos for the embedded instrumentation entities are created at the same time as the design protos itself, no changes to the BOM mechanism used for incremental compiles are required. The protos for the embedded instrumentation entities can be considered, for purposes of incremental compilations, to be mere extensions to the design proto itself.

[0172] The present invention discloses a method and system for naming events within a simulation model that prevents name collisions between events in different instrumentation entities, allows for the arbitrary re-use of components of a model in models of arbitrarily increasing size, and furthermore allows for processing designated events in a hierarchical or non-hierarchical manner.

[0173] When all instances of an event are considered as a whole without regard to specific instances, the event is considered in a “non-hierarchical” sense. Likewise, when an event is considered with regard to each and every instance, it is considered in a “hierarchical” sense. When considering count events, for example, it is often convenient to track the number of

times a particular count event occurred in the aggregate without concern to exactly how many times the count event occurred in each particular instance within a simulation model.

[0174] Each type of event: count, fail, and harvest, is given a separate event namespace by construction. Each event class is therefore an independent group preventing naming collisions between the event types. The data structure of the present invention is independently applied to each of the different event types to ensure correctness within each event class.

[0175] In the embodiments illustrated in Figures 10A, 10B, 10C, and 10D, the system and method of the present invention are described with respect to count events. One skilled in the art will appreciate and understand the extensions necessary to apply the same techniques to other event classes such as failures or harvests.

[0176] With reference to FIG. 10A, there is depicted a block diagram representation of simulation model 1000 containing a number of design and instrumentation entities. As illustrated in FIG. 10A, simulation model 1000 includes two instances of a design entity X, with instance names X1 and X2 respectively.

[0177] Within each of design entity instances X1 and X2 is instantiated an instance of an instrumentation entity B3, 1012a and 1012b. Design entity instances X1 and X2 further comprise instances, 1014a and 1014b, respectively, of design entity Z which further contains instances, 1016a and 1016b, of instrumentation entity B1 and instances, 1018a and 1018b, of instrumentation entity B2.

[0178] Finally, simulation model 1000 includes an instance of design entity Y, with instance name Y, containing an instance of instrumentation entity B4 1022. Design entity instance Y contains an instance, 1024, of design entity Z with further instances, 1016c and 1018c, of instrumentation entities B1 and B2 respectively.

[0179] In what follows the methods of the present invention for uniquely naming events will be considered in the context of exemplary model 1000. It will be assumed in the following description that each instrumentation entity (*B1*, *B2*, *B3*, and *B4*) has declared a single count event with event name “count1”.

[0180] In accordance with the method and system of the present invention, the user must uniquely name each type of event (count, fail, or harvest) within a specific instrumentation entity, i.e., the user cannot declare any two events of the same type within the same instrumentation entity with the same event name. Such a constraint does not conflict with the stated goals of the present invention in that a given instrumentation entity is usually created by a specific person at a specific point in time, and maintaining unique names within such a limited circumstance presents only a moderate burden to the user. The data structure disclosed herein does, however, prevent all name collisions between events in different instrumentation entities, and allows for processing the events in a hierarchical and/or non-hierarchical manner.

[0181] As previously explained, an HDL naming convention must uniquely identify all the entities within a given design. This constraint is inherent to HDLs and applies to design entities as well as instrumentation entities. In accordance with conventional VHDL entity naming constructs, it is technically possible for two design entities to share the same entity name, *entity\_name*. However, such identically named entities must be encapsulated within a VHDL library from which a valid VHDL model may be constructed. In such a circumstance, *entity\_name*, as it is utilized herein, is equivalent to the VHDL library name concatenated by a period (“.”) to the entity name as declared in the entity declaration.

[0182] Pre-pending a distinct VHDL library name to the entity name disambiguates entities sharing the same entity name. Most HDLs include a mechanism such as this for uniquely naming each design entity. Design entities must be unambiguously named in order to determine which particular entity is called for in any given instance in a simulation model. The present invention employs the prevailing naming mechanism of the native HDL to

assign unique entity names for design entities throughout a given model and leverages the uniqueness property of entity names and the uniqueness of each instance's instantiation identifier to create an "extended event identifier" for each event within the simulation model.

[0183] With reference to **FIG. 10B**, there is illustrated a representation of the fields in an extended event identifier data structure, alternatively referred to herein as an "event list", in accordance with one embodiment of the present invention. The extended event identifier begins with instantiation identifier field **1030**. This field, as described hereinbefore, consists of the instance identifiers, proceeding from the top level entity to the direct ancestor of the given instance within the simulation model separated by periods ("."). This string is unique for each and every instance of the event within the model. The extended event identifier further includes an instrumentation entity field **1032**, a design entity field **1034**, and an eventname field **1036**.

[0184] Instrumentation entity field **1032** contains the name of the instrumentation entity (or the name assigned to an embedded instrumentation entity) that generates the simulation event. Design entity field **1034** contains the entity name of the design entity in which the event occurs. Eventname field **1036** is the name given to the event in the instrumentation entity description comments of an instrumentation entity or the event name assigned to an event within an embedded instrumentation entity. These four namespace fields comprise a unique identifier for each event within a simulation model that allows for the re-use of components within other models without risk of name collisions and the consideration of events in a hierarchical or non-hierarchical sense.

[0185] With reference now to **FIG. 10C**, there is shown a list of extended event identifiers for model **1000**. Event identifiers **1040**, **1041**, **1042**, **1043**, **1044**, **1045**, **1046**, **1047**, and **1048** are declared within simulation model **1000** to designate count events having eventname "count1". The extended event identification procedure of the present invention will be described in the context of these extended event identifiers.

[0186] The uniqueness of the names in design entity name field **1034** is a primary distinguishing factor between events. By including the design entity name in the extended event identifier, each design entity is, in effect, given a unique namespace for the events associated with that design entity, i.e., events within a given design entity cannot have name collisions with events associated with other design entities.

[0187] It is still possible however, to have name collisions between events defined by different instrumentation entities that are incorporated within a single design entity. Events **1041** and **1042**, for example, if identified solely by the design entity name, have a name collision. Both are events with eventname “*count1*” within design entity *Z*, and if labeled as such, are indistinguishable. In order to alleviate a naming collision between events **1041** and **1042**, the present invention employs instrumentation entity field **1032**. By referencing the design entity and instrumentation entity names, both of which are unique with respect to themselves and each other, a unique event namespace is created for each instrumentation entity associated with any given design entity. For example, event identifier **1041** and **1042** would be in conflict (both named *Z.count1*), unless the respective instrumentation entity names are included within the extended event identifier to produce names *B1.Z.count1* and *B2.Z.count2* for these events.

[0188] It should be noted that it is possible to uniquely name each event by using instrumentation entity name field **1032** alone. Due to the uniqueness property of instrumentation entity names, event names that are only named by the instrumentation entity name and the event name field will be necessarily unique.

[0189] However, such a naming scheme is insufficient for associating events with a given design entity. In practice, it is desirable to associate events with the design entity in which they occur rather than associating them with the potentially numerous instrumentation entities that are utilized to track them. Moreover, referencing the appropriate design entity within the eventname allows all the events associated with a given design entity to be centrally referenced without the need to ascertain the names of all the instrumentation entities

associated with the given design entity. The data structure of the present invention utilizes both the instrumentation entity and design entity names in naming events for ease of reference at the cost of moderate uniqueness redundancy in the event names.

[0190] In an alternative embodiment of the present invention, the instrumentation entity name is not included within the extended event identifier. Referring to **FIG. 10D**, such an alternative extended event identification data structure is depicted. As shown in **FIG. 10D**, events are named by instantiation identifier field **1030**, design entity name field **1034**, and event name field **1036**.

[0191] Such a data structure provides name collision protection between design entities but not within design entities. That is, the user must ensure that events names for events associated with a given design entity do not collide. In case of user error in this regard, model build tools may be utilized to detect an event name collision condition during model compilation. The alternative data structure depicted in **FIG. 10D** provides for simpler naming and referencing of events at the expense of requiring the user to prevent name collisions for events associated with a given design entity.

[0192] Returning to **FIG. 10B**, the combination of instrumentation entity field **1032**, design entity name field **1034**, and eventname field **1036** for a given event, provides a unique identifier for any given event without regard to multiple instantiations of the event. In order to uniquely distinguish between multiple instantiations of an event, instantiation identifier field **1030** is included in the extended event identifier. Instantiation identifier field **1030** field, by its construction, provides a unique string for any instance of an entity within any simulation model.

[0193] When evaluating occurrences of an event in a non-hierarchical sense, instantiation identifier field **1030** is ignored while searching for matching events. As illustrated in **FIG. 10C**, for example, a non-hierarchical query for the number of time a “count1” event occurs

within design entity *Z* as detected by instrumentation entity *B1*, utilizes the following list of count eventnames:

X1.Z	B1	Z	COUNT1
X2.Z	B1	Z	COUNT1
Y.Z	B1	Z	COUNT1.

[0194] These count events are added together to form an aggregate count of the total number of time the specific event occurred within the simulation model.

[0195] A hierarchical query includes specific criteria to match against the hierarchy field to limit the counter or counters found to specific instances of the requested event. For example, a query to obtain the count1 event of instrumentation entity *B1* within the X1.Z instance of design entity *Z* utilizes the following count eventname:

X1.Z	B1	Z	COUNT1,
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which represents the number of times the count1 event was counted by instrumentation entity *B1* within design entity instance *X1.Z* for a particular simulation interval.

[0196] By providing matching model hierarchy criteria against instantiation identifier field 1030, it is possible to consider the events with respect to their particular instance or instances within the model, i.e., a hierarchical query. A non-hierarchical query merely ignores the hierarchy field and returns all the instances of the requested events within the model.

[0197] With reference to FIG. 11A, there is depicted a block diagram illustrating a simulation model 1100 in which the hierarchical event processing of the present invention is applicable. Simulation model 1100 comprises a top-level design entity 1130 in which a pair of lower-level design entities 1102 and 1120 is instantiated. A design entity 1104 containing instrumentation entity 1106 is included within design entity 1102. As illustrated in FIG. 11A, instrumentation entity 1106 includes logic 1110 for generating a simulation event 1108 from signal set 1132 from within design entity 1104. Design entity 1120 includes an instrumentation entity 1122 that generates a simulation event 1124 using signal set 1134.

[0198] Utilizing the techniques described hereinbefore, generating a hierarchical event that is some logical combination of events **1108** and **1124** requires the creation of an instrumentation entity associated with top level design entity **1130** that references signal sets **1132** and **1134**. Conventionally, such an instrumentation entity would substantially reproduce instrumentation logic **1110** and **1126** to process signal sets **1132** and **1134**, respectively, thus producing a copy of events **1108** and **1124**. Such a procedure is inefficient and prone to error. If, for example, changes are made to any or all of signal sets **1132** and **1134**, or instrumentation logic **1110** and **1126**, these changes would have to be accurately repeated in the instrumentation entity logic for the combined event.

[0199] The present invention provides a mechanism whereby events, such as events **1108** and **1124**, are directly referenced and utilized as inputs to cross-hierarchical instrumentation entities. In this manner, signal connections **1132** and **1134**, as well as instrumentation logic **1110** and **1126**, are directly re-utilized to produce the desired hierarchical event.

[0200] To facilitate direct referencing of events within simulation models, a specialized data structure is implemented within instrumentation entity input port map comment syntax. This data structure directly connects input ports of instrumentation entities to cross-hierarchical events within a simulation model.

[0201] For the embodiment depicted in FIG. 11A, an instrumentation entity **1150** is instantiated within top-level design entity **1130** to generate a hierarchical event **1156** that is some function of events **1108** and **1124**. As illustrated in FIG. 11A, instrumentation entity **1150** includes a pair of inputs **1151** and **1152** that are directly connected to events **1124** and **1108**, respectively, utilizing the augmented syntax described below. These input connections are logically combined using instrumentation logic **1154** to produce a cross-hierarchical event **1156**.

[0202] With reference to FIG. 11B, there is depicted a set of input port mapping comments for performing cross-hierarchical processing of simulation model events in accordance with the teachings of the present invention. In what follows, it is assumed that events 1108 and 1124 are count events with event names *event\_1108* and *event\_1124*, respectively, and that these events are connected to input ports *event\_1108\_in* and *event\_1124\_in* on instrumentation entity 1150. As depicted in FIG. 11B, a first input port mapping comment 1161 contains data for referencing event 1108 to input port *event\_1108\_in*. A second input port mapping comment 1162 contains data for referencing event 1124 to input port *event\_1124\_in*. It should be noted that each of input port mapping comments 1161 and 1162 includes a pre-pended non-conventional comment identifier, --!!, that is utilized by the HDL compiler (such as compiler 462 in FIG. 4D) to maintain the port mapping comments separate from the design.

[0203] To facilitate connection of a simulation event to an instrumentation entity input port, input port mapping comments 1161 and 1162 consist of two distinct parts: an instance identifier and an event identifier. The instance identifier is a string consisting of instance names (in descending hierarchical order) of all design entities between and including the design entity containing the instrumentation entity of the cross-hierarchical event being defined (i.e., the highest level design entity for the cross-hierarchical event), and the design entity in which the event that is utilized in generating the cross-hierarchical event. If the design entity containing the hierarchical event is the same as the design entity containing the event to be connected to, the instance identifier is a null string. A pair of instance identifiers 1163 and 1164, within input port mapping comments 1161 and 1162, respectively, specifies that events 1124 and 1108 originate from signals within design entity 1120 and 1104 respectively.

[0204] Input port mapping comments 1161 and 1162 further include event identifiers 1165 and 1166, that identify input simulation events in terms of local instrumentation entities 1106 and 1122, respectively. In accordance with the embodiment depicted in FIG. 11B, each event identifier consists of a string beginning with an open bracket (“[“) character and ending

with a closed bracket (“]”) character. Between these brackets, three sub-strings, delineated by period (“.”) characters, comprise a data structure utilized to identify a specific event from which the cross-hierarchical event is defined. The first sub-string within an event identifier is the instance name of the instrumentation entity containing the event. The second sub-string is a string specifying the type of the event (“count”, “fail”, or “harvest”). Finally, the third sub-string is the event name of the given event as specified in the declaration comment for the event. Each event identifier string uniquely identifies a single event within a given design entity. As depicted in FIG. 11B, event identifier strings 1165 and 1166 identify events 1108 and 1124 respectively.

[0205] In accordance with an alternate embodiment of the present invention, the event identifier naming structure is modified slightly for events that are labeled in accordance with FIG. 10D (event names that do not include the instrumentation entity name). When an instrumentation identifier is absent from the extended event identifier, the event identifier string with an input port mapping comment consists of two sub-strings: a string denoting the type of event to connect to; and a string providing the name of the event separated by a period (“.”) character. The instrumentation entity name is not required in this case since all events of a given type associated with a given design entity will have unique names. The model build tools of the present invention will automatically search all instrumentation entities associated with the design entity called out by the instance identifier to determine which instrumentation entity generates an event having the name and type provided in the event identifier string.

[0206] Referring to FIG. 11C, there is illustrated a set of data structures for performing hierarchical processing of simulation model events in accordance with a second embodiment of the present invention. In the depicted embodiment, a pair of input port mapping comments 1171 and 1172 employs a syntax compatible with the event naming data structure depicted in FIG. 10D.

[0207] Input port mapping comment 1171 connects event 1108 to input port *event\_1108\_in* on instrumentation entity 1150. Likewise, input port mapping comment 1172 connects event 1124 to input port *event\_1124\_in* on instrumentation entity 1150. By utilizing the augmented syntax of **FIG. 11B** or **FIG. 11C** it is possible to create hierarchical events by connecting the inputs of instrumentation entities to events within the simulation model.

[0208] The above described system and method provides for practical instrumentation of simulation models and allows for efficient implementation of instrumentation logic through embedded instrumentation entities. Embedded instrumentation entities, as described hereinabove, are however necessarily limited to task-specific implementations. As described with reference to Figures 12A and 12B, the present invention further provides for a more flexible implementation of instrumentation logic in a more unstructured manner.

[0209] It is often necessary to tailor instrumentation logic to address unique problems and circumstances. Instrumentation logic of a specific and yet non-predefined nature that is designed in accordance with the techniques disclosed herein with reference to Figures 12A and 12B is referred herein as “random instrumentation logic.” A data construct consisting of general logic primitives (Boolean operators, storage elements, etc.) and an interconnection method for these primitives is utilized for implementing such random instrumentation logic.

[0210] For instrumenting a simulation model as described heretofore, an HDL such as VHDL or Verilog is utilized as a platform from which instrumentation logic is generated. Appropriate instrumentation entity descriptor comments within design entity source code files couple the resultant instrumentation entities to designated target design entities within a simulation model.

[0211] In addition to entity descriptor comments within a design entity source code file, the foregoing instrumentation technique requires a separate HDL file in which the instrumentation entity is described. As explained with reference to Figures 12A and 12B, the present invention provides a method, system, and data structure for instrumenting design

entities within a simulation model while avoiding the design process overhead required for creating a separate instrumentation entity HDL file.

[0212] In accordance with the teachings of the present invention, random instrumentation logic is directly deployed within target design entities in terms of individualized and customizable instrumentation descriptor comments. Such instrumentation descriptor comments are encoded within the target design entity HDL source code file and provide a means for the describing random instrumentation logic, events, and interconnections between the created instrumentation logic and the target design entity. The random instrumentation logic is inserted into the simulation model in a manner similar to the techniques used for embedded instrumentation entities to produce an instrumentation entity without the need for the creation of an explicit HDL instrumentation entity file.

[0213] With reference to **FIG. 12A**, there is illustrated a representative target design entity **1200** wherein random instrumentation logic is implemented in accordance with a preferred embodiment of the present invention. Instantiated within target design entity **1200** is a design entity **1201**. As further depicted in **FIG. 12A**, an instrumentation entity **1202** is instantiated within design entity **1201**. Instrumentation entity **1202** is designed in accordance with the principles set forth hereinabove to generate a count event **1203** having an event name “count1.” Target design entity **1200** further includes an instrumentation entity **1208** that is generated utilizing random instrumentation logic. As depicted in **FIG. 12A**, instrumentation entity **1208** receives as inputs signals *P*, *A*, *B*, and *C* along with count event **1203**.

[0214] Instrumentation entity **1208** is constructed by a set of unconventional comments lines within the source code file for target design entity **1200**. These comments may be incorporated at any point within the logic description section of the HDL source code file. HDL compiler **462** (**FIG. 4B**) recognizes the unconventional comments in addition to any comments utilized to instantiate embedded instrumentation entities within design entity **1200**. During the post-compilation/model build phase, instrumentation load tool **464** processes

these comments in a manner similar to that utilized for embedded instrumentation entities (described with reference to Figures 10A-10D) to generate instrumentation entity 1208.

[0215] A variety of possible syntaxes can be utilized to formulate the unconventional HDL comments required for generating random instrumentation logic within the source code file of a target design entity. As depicted in Figure 12B, much of the syntax of these comments employs syntax similar to the concurrent subset of the VHDL language with the addition of syntactic and semantic enhancements that provide a means of connection between an instrumentation entity and its target design entity. In addition, minor syntactic and semantic enhancements are provided to declare events and intermediate signals.

[0216] With reference now to FIG. 12B, there is illustrated an exemplary HDL source code file 1220 that describes design entity 1200. Within HDL source code file 1220, an entity instantiation 1221 produces design entity 1201, and assignment statements 1222 are utilized to generate signals *A*, *B*, and *C*. A set of unconventional comments 1223 within HDL source code file 1220 is utilized to produce instrumentation entity 1208. Comments 1223 are formulated as left-hand side (l.h.s.)/right-hand side (r.h.s.) assignment statements of the form:

{l.h.s.} <= {r.h.s.};

where {l.h.s.}, referred to herein after as *lhs*, is the assignment statement target and, {r.h.s.}, referred to herein after as *rhs* is an expression denoting the logical value to be assigned to the statement *lhs*. A number of rules delineate the possible expressions for *lhs* and *rhs* in any legal statement in the instrumentation comments.

[0217] As employed within the instrumentation data structure of the present invention, a *lhs* statement may be either an event declaration or the name of a signal that is instantiated within an instrumentation entity. An event declaration is an expression within bracket characters (“[”, “]”) that generates a new event. Within comments 1223, a statement 1230 produces a count event 1240 from instrumentation entity 1208 (FIG. 12A) having eventname “countname0”.

[0218] Within an *lhs* event declaration, a first field designates the event type (count, fail, harvest, etc.) and is followed by such other fields as are necessary to declare the event. As illustrated in lines 1230, 1234, and 1236, such event declaration fields follow the same format as the event declaration fields depicted in FIG. 4C.

[0219] Comments 1223 further include a line 1232 having an *lhs* that declares a signal *Q* within instrumentation entity 1208. To prevent ambiguity, any signal declared in this manner may not have a name corresponding to the name of any signal present on the top level of target design entity 1200. Conformance to this requirement is verified by instrumentation load tool 464 (FIG. 4D) during processing. Signals declared by an *lhs* expression may be incorporated within an *rhs* expression as shown in lines 1232 and 1234.

[0220] An *rhs* consists of logical connectivity expressions and/or functions that combine various signals. Signals within these connectivity expressions may originate from a number of possible sources including: signals declared on the *lhs* of a statement in the instrumentation comments; signals within the target design entity; or signals designating other events within the target design entity.

[0221] The absence of period (“.”) or bracket (“[”, “]”) characters within a signal value description in the *rhs* of a statement, designates the object signal as corresponding to either a signal within the top hierarchical level of the target design entity or to a signal declared on the *lhs* of a statement within the instrumentation language. Signals are named in a mutually exclusive manner by the rules governing creation of signals on the *lhs* of a statement in the instrumentation comments, thereby preventing any ambiguity in the determining the source of the given signal.

[0222] Signals in *rhs* connectivity expressions can also be connections to signals within entities instantiated within the target design entity. In such a circumstance, the instance names of the entity or entities in the hierarchy enclosing the desired signal are placed before

the signal name in hierarchy order, delineated by period (“.”) characters. For example, the signal in statement **1230** (“Y.P”) represents signal **1204** within design entity **1201**. Signals at any level of the target design hierarchy are thus accessible to instrumentation logic generated by the instrumentation language comments.

[0223] Signals within the instrumentation comment expressions can also designate other events within the target entity. Event identifiers as described hereinbefore for hierarchical events are used to denote such “event” signals. For example, statement **1232** performs a logical AND of instrumentation event **1203** and signal *A*. The event identifier “Y.[B1.count.count1]” connects instrumentation entity **1208** to instrumentation event **1203**. This notation permits instrumentation events at any level of design hierarchy within target design entity **1200** to be directly accessed.

[0224] As further depicted in **FIG. 12B**, statement **1232** produces intermediate signal *Q* within instrumentation entity **1208**. This is an example of an instrumentation comment statement declaring a new intermediate signal. These signals can be used in other statements to construct random instrumentation logic of any desired depth or complexity.

[0225] Statement **1234** utilizes intermediate signal *Q* along with signal **1206** to produce fail event **1241**. The syntax for fail event declaration includes a field denoting the type of event (“fail”), a field giving the event name for the fail event (“failname0”), and a final field denoting the message to associate with the fail. Finally, statement **1236** produces harvest event **1242**.

[0226] In general, the *rhs* expression of any statement in the instrumentation data structure of the present invention can access any signal or instrumentation event signal within the target design entity utilizing these syntactic mechanisms. These signals can be combined to form new events or intermediate signals that can themselves be further combined to form instrumentation logic of any desired depth or complexity.

[0227] Instrumentation comments can be placed anywhere within the logic description section of the target entity source code file. All instrumentation comments within a file are considered as a whole and produce a single instrumentation entity within the target design entity.

[0228] As noted briefly above, it is frequently useful to generate trace files during simulation so that further analysis of simulation results can be performed “offline” after a simulation run has completed. Availability of trace files after simulation has completed simplifies certain types of logical checks and permits trace analysis programs to easily scan the trace data forwards and backwards to locate events of interest.

[0229] In order to facilitate the creation of trace files during simulation, the present invention provides a language construct that permits a user to easily instrument a simulation model with a trace array that stores trace data regarding events of interest within the simulation model. In accordance with an important aspect of the present invention, the language construct defining the trace array is set forth within an HDL file defining a design or instrumentation entity, thereby associating the trace array with that entity. In this manner, the software tools hereinbefore described automatically replicate a trace array and associated support logic for every instance of the entity with which the trace array is associated.

[0230] Referring now to FIG. 13, there is depicted an implementation of an exemplary simulation model including trace arrays in accordance with the present invention. As illustrated, simulation model 1302, which may be built in either the volatile memory of a software simulator or in the hardware of a hardware simulator in accordance with the process depicted in Figure 4D, includes a number of hierarchically arranged design and instrumentation entities. In particular, simulation model 1302 includes a top-level entity 1304 (having the description TOP:TOP), which contains instantiations 1310a and 1310b of entity A and instantiation 1312 of entity B. Each of instantiations 1310a, 1310b of entity A in turn instantiates a respective one of instantiations 1316a, 1316b of entity C and a

respective one of instantiation **1314a**, **1314b** of instrumentation entity **A\_CHK**. Instantiation **1312** of entity **B** similarly instantiates instantiation **1318** of instrumentation entity **B\_CHK**.

[0231] In accordance with the present invention, instrumentation entity instantiations **1314a**, **1314b** and **1318** are each equipped with a respective one of trace arrays **1320a**, **1320b** and **1322**. Each of trace arrays **1320a**, **1320b** and **1322** has a input data bus comprised of signals to be traced. Thus, for example, each trace array **1320** within an instantiation **1314** of instrumentation entity **A\_CHK** receives a ten-bit input data bus formed of a four-bit signal  $X(0..3)$  **1330**, a five-bit signal  $Y(0..4)$  **1332**, and a one-bit signal  $Z$  **1334**. Similarly, trace array **1322** within instantiation **1318** of instrumentation entity **B\_CHK** receives a five-bit input data bus comprised of four-bit signal  $D(0..3)$  **1336** and one-bit signal  $E$  **1338**.

[0232] As further illustrated in **Figure 13**, each trace array may optionally have a user control input (CTRL), as described further below, and has a respective FULL output signal **1340a**, **1340b** and **1342**. FULL output signals **1340a**, **1340b** and **1342** are asserted by the associated trace array when the trace array is full of trace data and must be emptied. All FULL signals **1340a**, **1340b** and **1342** form inputs of OR GATE **1344**, which performs a logical OR operation on its input signals to generate trace status signal **1346**. Trace status signal **1346** is, in turn, received as one of the inputs of OR GATE **515**, which as described above with reference to **Figure 5B**, asserts a halt signal **516** if a simulation run has completed (i.e., signal **513** is asserted), if a failure event has occurred (i.e., signal **511** is asserted), or if trace status signal **1346** is asserted. If halt signal **516** is asserted, simulation by the hardware or software simulator on which simulation model **1302** is running is halted, and if trace status signal **1346** is asserted, empties at least each trace array **1320a**, **1320b**, **1322** asserting its FULL signal **1340a**, **1340b**, **1342** (and optionally all trace arrays in simulation model **1302**). In this manner, a Run Time eXecutive (RTX) program controlling a simulation run will be notified by simulation model **1302** when trace data needs to be emptied from a trace array, thus avoiding the simulation performance degradation that would occur if trace data were captured from the simulation model more frequently than necessary (e.g., every cycle).

[0233] Still referring to **Figure 13**, simulation model **1302** further includes a trace array table **1350**. Trace array table **1350** is a data structure that centralizes information about each trace array instance within simulation model **1302** in a single location to permit API routines to easily locate and access each trace array within simulation model **1302**. Trace array table **1350** is preferably created at model build time by model build tool **446** (**FIG. 4D**) from information obtained by HDL compiler **462** from trace array declarations within the HDL source code files describing the design and instrumentation entities comprising simulation model **1302**.

[0234] In a preferred embodiment, trace array table **1350** identifies each trace array by both its designer-defined eventname (e.g., `a_trace` for both trace arrays **1320a** and **1320b**) and its associated hierarchical instance name (e.g., `TOP.A0.A_CHK` for trace array **1320a**). In addition, trace array table **1350** preferably lists the subfields (i.e., constituent signal groups) in each trace array by name and the bit locations of the subfields in the overall trace array. Finally, in embodiments of the present invention supporting multiple different types of trace arrays, trace array table **1350** indicates the type of each trace array. In the exemplary embodiment, three types of trace arrays are supported:

- 1) uncontrolled – the trace array samples the input data bus every cycle and does not support user control (and hence has no input CTRL signal);
- 2) controlled – the trace array samples the input data bus only on the simulation cycles that the input CTRL signal is pulsed by user logic and stores the samples in chronological order, but does not indicate the time intervals between the samples; and
- 3) controlled and timed – the trace array samples the input data bus only on the simulation cycles that the input CTRL signal is pulsed and further maintains an indication of the number of simulation cycles between successive trace samples.

[0235] With reference now to **Figure 14**, there is illustrated a more detailed block diagram of an exemplary embodiment of a controlled and timed trace array **1320** in accordance with one embodiment of the present invention. As illustrated, trace array **1320** includes a plurality of

entries **1402a-1402n** for storing respective samples of the signals comprising input data bus **1401**. Trace array **1320** further includes control logic **1410**, which controls the sampling of input data bus **1401**. In particular, control logic **1410** asserts WRITE signal **1422** in response to assertion of CTRL signal **1420** by user logic in order to cause a sample of input data bus **1401** to be captured and written in an entry **1402**. Control logic **1410** also specifies the entry **1402** into which the sample of input data bus **1401** is written by outputting an index signal **1424** identifying the selected entry **1402**. As samples are captured and stored within succeeding entries **1402**, control logic **1410** increments an internal index counter and, when control logic **1410** determines that entries **1402** have all been written, asserts FULL signal **1340**, as described above with reference to **Figure 13**.

[0236] Controlled and timed trace array **1320** further includes counter logic **1412**. Counter logic **1412** contains a counter (e.g., an LFSR or incrementer) **1414** that tracks the elapsing of time since the immediately previous entry **1402** was written. When control logic **1410** asserts WRITE signal **1422**, control logic **1410** also causes counter logic **1412** to store the value of counter **1414** within a count field **1408** of the entry **1402** that is written. If counter **1414** reaches its maximum value without a new entry **1402** being written, counter logic **1412** writes the maximum count value within count field **1408** of a new entry **1402**, and control logic **1410** sets an overflow bit within the associated overflow field **1404** and updates its internal index counter. Such an overflow entry **1402** records no trace data, but records the passage of time during the simulation run. After counter logic **1412** writes the value of counter **1414** into the count field **1408** of an entry **1402** either through occurrence of an overflow or in conjunction with writing a sample of input data bus **1401**, counter logic **1412** resets counter **1414** to begin counting the next time interval.

[0237] As noted above, **Figure 14** depicts an embodiment of a controlled and timed trace array **1320**. The other types of trace arrays can be implemented similarly, but require less logic. For example, controlled trace arrays omit counter logic **1412**, overflow field **1404** and count field **1408** since no timing is performed. Uncontrolled trace arrays can omit these

elements and can further omit CTRL signal **1420** because the control logic of uncontrolled trace arrays is configured to sample the input data bus each simulation cycle.

[0238] Referring now to **Figure 15**, there is illustrated a high-level logical flowchart of an exemplary process by which an RTX directs the execution of a testcase against a simulation model containing trace arrays in accordance with the present invention. The illustrated process is applicable to simulation models implemented within either a software simulator or a hardware simulator.

[0239] As shown, the process begins at block **1500**, which represents the RTX beginning a simulation run of a testcase against a simulation model, for example, in response to an input by a simulation user. The process proceeds from block **1500** to block **1502**, which depicts the RTX calling the entry point of an API routine to reset and clear all of the trace arrays within the simulation model. In particular, the API routine preferably clears all of the entries **1402**, and resets the index counters and time counters **1414** (if applicable) in each trace array. Following the initialization performed at block **1502**, the process depicted in **Figure 15** proceeds to block **1504**, which illustrates the RTX initiating execution of the testcase against the simulation model. During the execution, the RTX determines at block **1506** whether or not halt signal **516** is asserted. If the simulation is running on a software simulator, the RTX preferably polls halt signal **516** each simulation cycle to determine whether or not simulation should be halted. Alternatively, if the simulation is being run on a hardware simulator, assertion of halt signal **516** will halt simulation by the hardware simulator automatically. Accordingly, during execution of the testcase, the process illustrated in **Figure 15** iterates at block **1506** until halt signal **516** is asserted.

[0240] In response to the assertion of halt signal **516**, the process proceeds from block **1506** to block **1508**. Block **1508** illustrates the RTX examining trace status signal **1346** to determine whether or not halt signal **516** was asserted due to the assertion of trace status signal **1346**. If trace status signal **1346** was not asserted, the process passes to block **1512**, which is described below. If, however, the RTX determines at block **1508** that halt signal

**516** was asserted due to the assertion of trace status signal **1346**, the process proceeds to block **1510**.

[0241] Block **1510** illustrates the RTX calling the entry point of an API routine that dumps the trace data from each trace array instance in the simulation model to a respective trace file, which may be stored, for example, in non-volatile storage. In order to dump the trace data from the trace arrays into trace files, the API routine called at block **1510** enters trace array table **1350** and, as indicated in block **1510**, performs three main processing steps for each trace array listed within trace array table **1350**. In particular, the API routine creates a trace file for the trace array instance if one does not already exist, dumps the trace data from the trace array instance if the trace array instance contains any trace data, and resets control logic **1410** and counter logic **1412** for the trace array.

[0242] As will be appreciated by those skilled in the art, the trace files created by the API routine may have any of a wide variety of formats. **Figure 16** illustrates an exemplary trace file **1600** employing one such format. As depicted, trace file **1600** includes three header fields: a version field **1602** that identifies the version of the trace file format to support backwards compatibility, an array-type field **1604** indicating the array type (e.g., uncontrolled, controlled, or controlled and timed) specified for trace array table **1350** for the associated trace array, and subfields **1606** that identify the various subfields in the trace file data and which bits within the trace data correspond to each subfield. In addition, as discussed further below, subfields **1606** include an enum map **1608** that associates selected enumerated values with particular subfield bit values. Like the contents of array type field **1604**, the contents of subfields **1606** and enum map **1608** are obtained directly from trace array table **1350**.

[0243] Following subfields **1606**, trace file **1600** contains trace data **1610** dumped by the API routine to trace file **1600**. As would be expected, the format of trace data **1610** varies with the type of trace array, but generally contains the contents of entries **1402a-1402n** from a trace array appended sequentially to previous dumps of that trace array.

[0244] Returning to **Figure 15**, after each trace array instance within the simulation model has been processed at block **1510** or in response to a negative determination at block **1508**, the process depicted in **Figure 15** proceeds to block **1512**. Block **1512** illustrates the RTX determining whether or not fail signal **511** was asserted to signal detection of an occurrence of a fail event. If an occurrence of fail event was detected within the simulation model, as indicated by assertion of fail signal **511**, execution of the testcase terminates with a fail status at block **1514**. If, however, fail signal **511** was not asserted, the RTX makes a further determination at block **1516** whether or not termination signal **513** was asserted to indicate that simulation of the testcase has completed. In response to a determination that termination signal **513** was not asserted, meaning that execution of the testcase against the simulation model has not completed, the process returns to block **1504**, representing the RTX instructing the simulator to resume testcase execution. If, however, RTX determines that termination signal **513** was asserted to signal that the end of the testcase has been reached, the process proceeds to block **1516**, which depicts the RTX calling an entry point of an API to close the trace files opened in block **1512**. Thereafter, the process shown in **Figure 15** terminates at block **1520**.

[0245] With reference now to **Figure 17**, there is illustrated a high level block diagram of a post-processing environment in which a trace analysis tool accesses and processes trace files created in accordance with the simulation process illustrated in **Figure 15**. As illustrated, the post-processing environment includes a trace analysis tool **1700**, which may or may not form part of the RTX. Trace analysis tool **1700** includes a set of trace reader APIs **1702** that read trace files **1600** created within non-volatile storage **1704**. In order to facilitate access to selected trace files **1600** by trace reader APIs **1702**, trace files **1600** within non-volatile storage **1704** are preferably given file system names based upon the instance names listed in trace array table **1350** for the associated trace arrays. Moreover, all trace files **1600** from a particular simulation run are preferably deposited in a dedicated subdirectory of non-volatile storage **1704** in order to prevent the file system names of trace files from different simulation runs from colliding.

[0246] Importantly, because each trace file 1600 preferably includes a version field 1602, an array type field 1604 and subfields 1606, trace reader APIs 1702 have within trace file 1600 all information needed to interpret trace data 1602. Consequently, trace analysis tool 1700 is insulated from the need to understand the details of trace files 1600, as long as trace reader APIs 1702 are designed to correctly interpret the header fields of the trace files 1600.

[0247] As will be appreciated by those skilled in the art, any number of syntaxes may be designed to declare trace arrays to be instantiated within a simulation model as hereinbefore described. In accordance with the present invention, any of these syntaxes may be employed to declare trace arrays within the HDL source code files describing the design and instrumentation entities comprising the simulation model. However, in order to promote understanding of the present invention, two exemplary syntaxes are described below.

[0248] The first exemplary syntax permits a designer to explicitly declare a trace array within a set of instrumentation entity descriptors in an HDL instrumentation entity file, in accordance with the syntax described above with respect to FIG. 4C. For example, in order to declare a trace array 1320 within each of instantiations 1314a, 1314b of instrumentation entity A\_CHK, the HDL instrumentation entity file of A\_CHK may be given as follows (line numbers are included only for ease of reference and are not part of the HDL):

ENTITY A_CHK IS	5
PORT (	
X_IN : IN std_ulogic_vector(0..3);	10
Y_IN : IN std_ulogic_vector(0..4);	15
Z_IN : IN std_ulogic;	
... other ports as required ...	20
);	25
--!! BEGIN	30
--!! Design Entity: A;	35
--!! Inputs	40
--!! X_IN => X(0..3);	45
--!! Y_IN => Y(0..4);	50

--!! Z_IN => C.Z;	55
--!! :	60
--!! End Inputs	65
--!! Trace Array	70
--!! [a_trace, controlled_timed, a_ctrl, 256] {	75
--!! Field: field1	80
--!! X(0..3)	85
--!! Enum1 = b'0000'	90
--!! Enum2 = x'F'	95
--!! Field: field2	100
--!! Y(0..4)	105
--!! C.Z	110
--!! Cat = b'0000001'	115
--!! Dog= x'3F'	120
--!! };	125
--!! End Trace Array	130
--!! End	135
ARCHITECTURE example of A_CHK IS	140
BEGIN	145
... HDL code for entity body section ...	150
END;	155

**[0249]** In this exemplary HDL instrumentation entity file, the I/O ports of an A\_CHK instrumentation entity are declared in the entity declaration set forth at lines 5-25. Next, lines 30-35 contain a prologue and target entity name that indicate that the instrumentation entity description has begun and identify the name of the particular target design entity (e.g., design entity A) in which the instrumentation entity will be instantiated. Thereafter, at lines 40-65 an input port map specifies a connection between the input ports of the instrumentation entity and the signals to be monitored within the target design entity (or one of its descendants).

**[0250]** Following the input port map, the set of instrumentation entity descriptors includes a trace array declaration section at lines 70-115, which, as shown, is bounded by delimiter comments of the form “--!! Trace Array” and “--!! End Trace Array”. At line 75, the trace array for instrumentation entity A\_CHK is declared utilizing multiple fields bounded by

brackets “[]”. Within the brackets, the first field is the “eventname” of the trace array (e.g., `a_trace`), the second field indicates the type of trace array (e.g., “controlled\_timed”, “controlled”, or “untimed”), the third field specifies the name of the control signal that controls when the input data bus is sampled, and the optional final field indicates a suggested number of entries **1402** in the array. The tools shown in **FIG. 4D** may or may not allocate the specified number of entries **1402** in the trace array based on available resources and computational convenience (e.g., the tools may constrain trace array sizes to powers of 2).

[0251] Following the trace array declaration at line 75, subfield descriptions are given at lines 80-125. Specifically, at line 80, a first subfield (i.e., `field1`) is declared. `Field1` consists of the signal(s) listed until the next subfield declaration or the end of this trace array declaration, meaning that in the present case `field1` consists of signal `X(0..3)`. At line 100, a second subfield (i.e., `field2`) is similarly declared, which consists of the 6 bits of signals `Y(0..4)` and then `C.Z` (in that order). The signals belonging to a subfield can include any signal within the target design entity or any of its descendants. In addition, other “events” specified in accordance with **FIGS. 11B** and **11C** may also be declared as belonging to a subfield. Each such event is defined as a 1-bit signal.

[0252] Because enumerated values (e.g., text strings) are generally easier for a human user to understand than bit strings, subfield declarations may further associate particular values of a subfield with a designer-selected enumerated value. For example, at lines 90-95, the value of signal `X(0..3)` of `b'0000'` is assigned the enumerated value `Enum1`, and the value of signal `X(0..3)` of `x'F'` is assigned the enumerated value of `Enum2`. Enumerated values are similarly assigned to values of subfield `field2` at lines 115-120. As described above, the designer-selected enumerated values, if any, for each subfield are stored within trace array table **1350** of the simulation model **1302** and in enum map **1608** of trace files **1600**.

[0253] Similar syntax to that given above may also be utilized to declare trace array **1322** within `B_CHK` entity **1318**. For example, if trace array **1322** is an uncontrolled trace array,

the trace array declaration section of the HDL instrumentation entity file of B\_CHK may be given as:

--!! Trace Array	5
--!! [b_trace, untimed, 128] {	10
--!! Field E	15
--!! D(0..3)	20
--!! E	25
--!! };	30
--!! End Trace Array	35

Note that the trace array declaration for trace array **1322** at line 10 does not contain an identifier of a control signal since trace array **1322** is uncontrolled.

**[0254]** A second syntax that may alternatively or additionally be employed to declare trace arrays within HDL source code files is the “in-line” event declaration format described above with reference to **FIG. 12B**. If this second syntax is employed, the trace array declaration is placed within the HDL source code file of the instantiating design entity rather than within an HDL instrumentation entity file (e.g., the HDL source code file of design entity A rather than instrumentation entity A\_CHK). In addition, small syntactical modifications are made to the first syntax described above in order to comport with the in-line event declaration format described above.

**[0255]** For example, if the in-line event declaration format is employed, trace array **1320** may alternatively be declared within the HDL source code file of design entity A utilizing the following trace array declaration:

```
--!! [trace, a_trace, controlled_timed, a_ctrl, 256] {
--!! Field: field1
--!! X(0..3)
--!! Enum1 = b'0000'
--!! Enum2 = x'F'
--!! Field: field2
--!! Y(0..4)
--!! C.Z
```

```
--!! Cat = b'000001'  
--!! Dog= x'3F'  
--!! };
```

[0256] As can be observed, the in-line event declaration syntax is identical to the alternative syntax described previously, except for two modifications. First, the bracketed declaration of the trace array is augmented within an additional event type field, which in this case has the value “trace” to identify the event declaration as that of a “trace” event. Second, in view of the augmentation of the trace array declaration with an explicit field having the value “trace,” the delimiting “--!! Trace Array” and “--!! End Trace Array” comments are omitted as extraneous.

[0257] As has been described, the present invention provides an improved technique for declaring and implementing trace arrays in a simulation model of a digital design. In accordance with the invention, a designer declares a trace array utilizing one or more statements within at least one HDL source code file describing an entity within the simulation model. An HDL compiler and other software tools thereafter parse and processes the HDL source code files (including the trace array declaration statement(s)) to generate a simulation model including a trace array and representations of the entities comprising the simulation model. Once the simulation model is created, a software or hardware simulator runs a testcase against the simulation model, and during the simulation run, records trace data within the trace array in the simulation model. As the trace array is filled with trace data, the trace data are exported into trace files, which may be stored in non-volatile storage for later examination and analysis.

[0258] While the invention has been particularly shown as described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention. One of the embodiments of the invention can be implemented as sets of instructions resident in random access memory **28** of one or more computer systems configured generally as described in **FIG. 1** and **FIG. 2**. Until required by computer system

**10**, the set of instructions may be stored in another computer readable storage device, such as disk drive 33 or in a removable storage device such as an optical disk for eventual use in a CD-ROM drive or a floppy disk for eventual use in a floppy disk drive. The set of instructions may be referred to as a computer program product. Further, the set of instructions can be stored in the memory of another computer and transmitted over a local area network or a wide area network, such as the Internet, when desired by the user. It is therefore contemplated that such modifications can be made without departing from the spirit or scope of the present invention as defined in the appended claims.